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The Society functions for the promotion of the science of geophysics as it is related to petroleum geology and the production of oil and gas and associated minerals, to mining geology, and to the maintenance of a high professional standard among its members. Among the methods of accomplishing these objectives is the publication of papers, discussions, and communications of interest to the membership.

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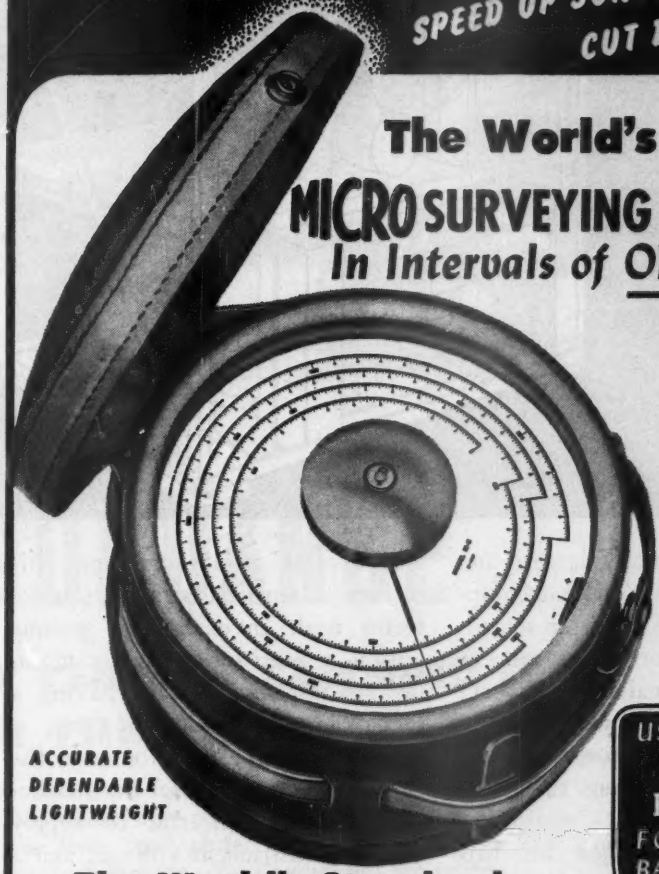

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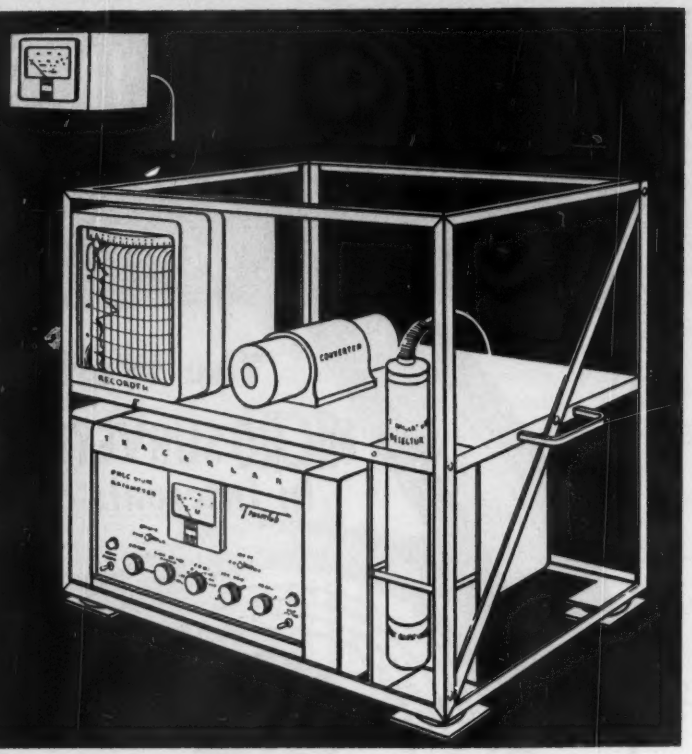

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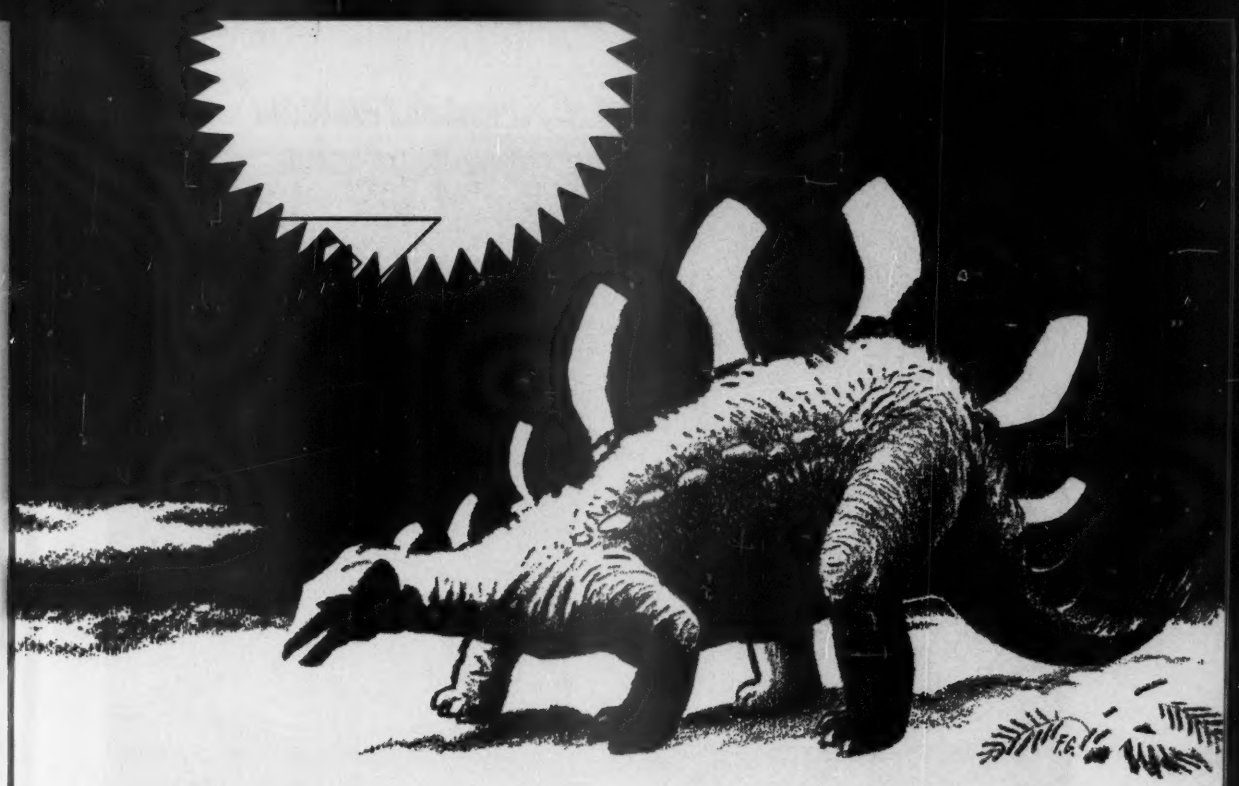

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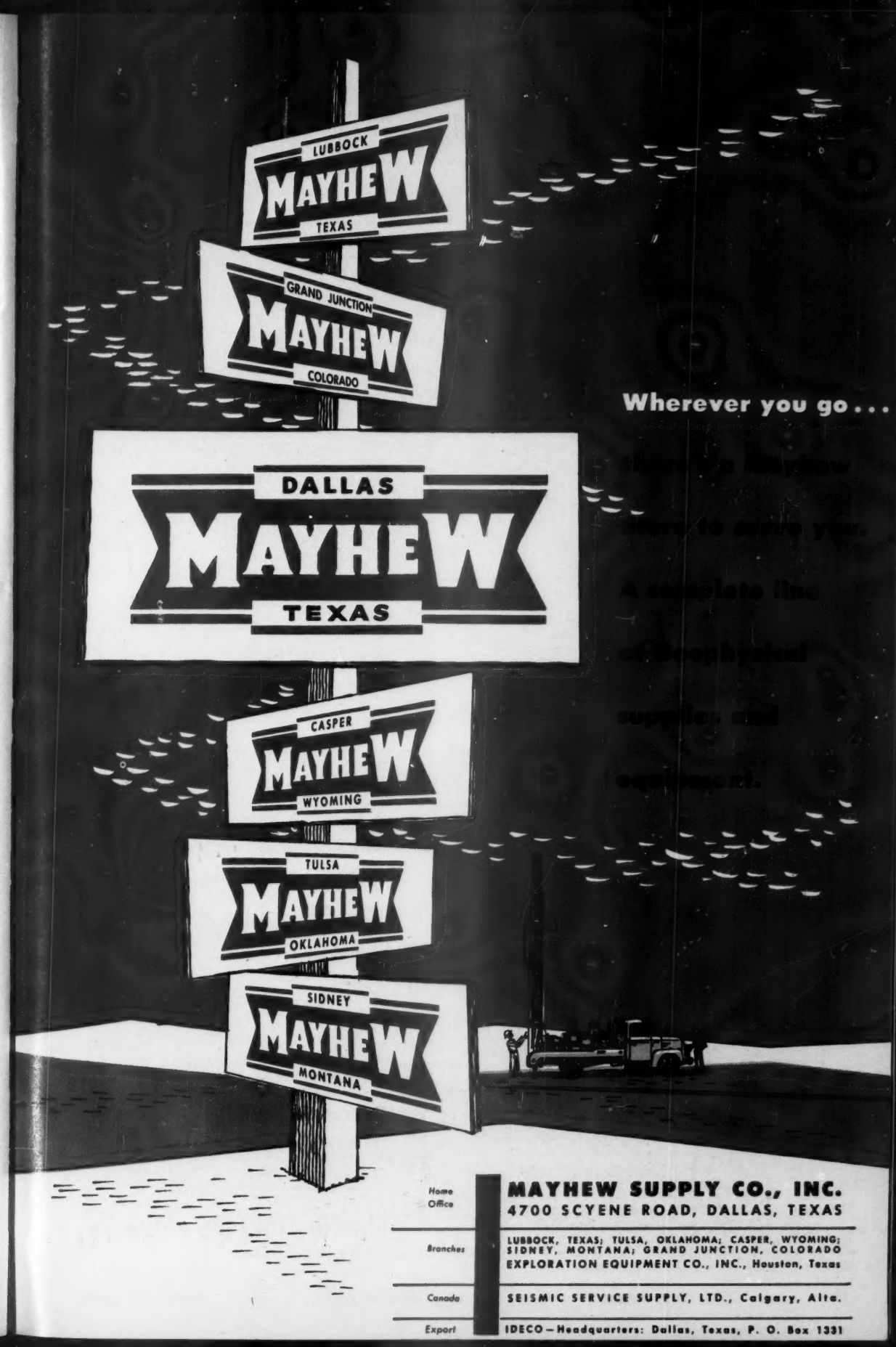

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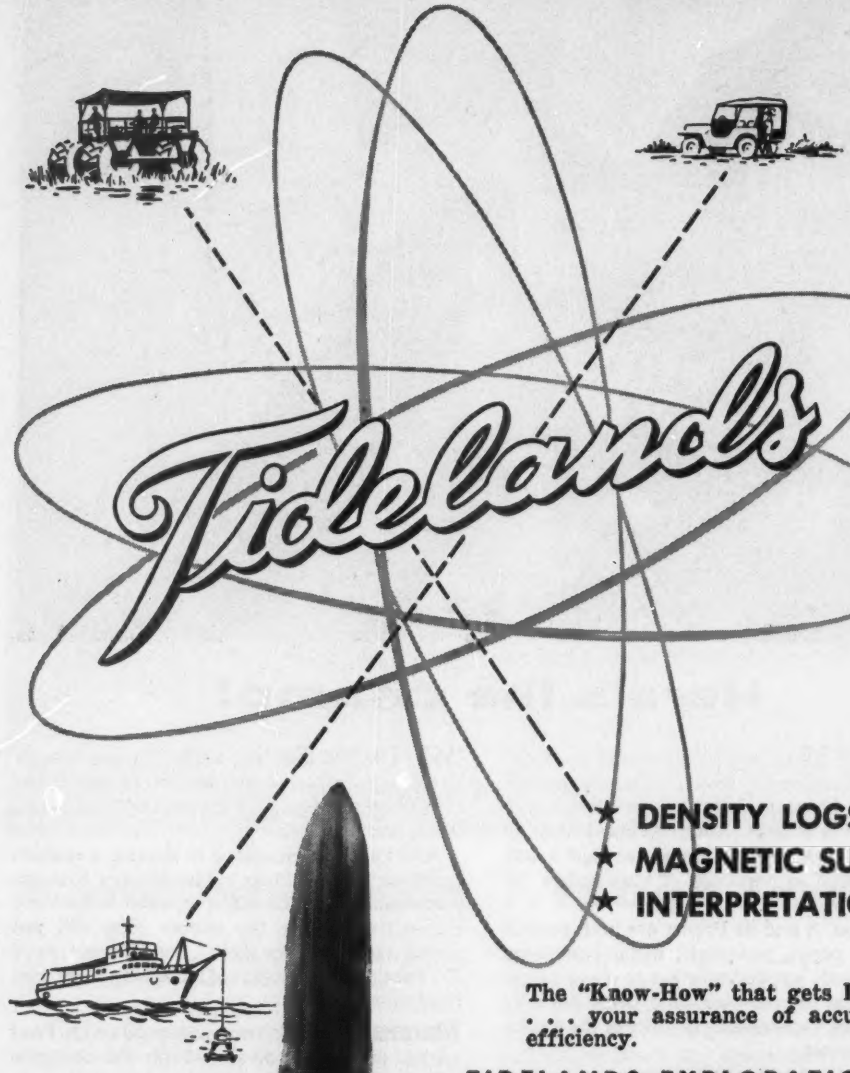

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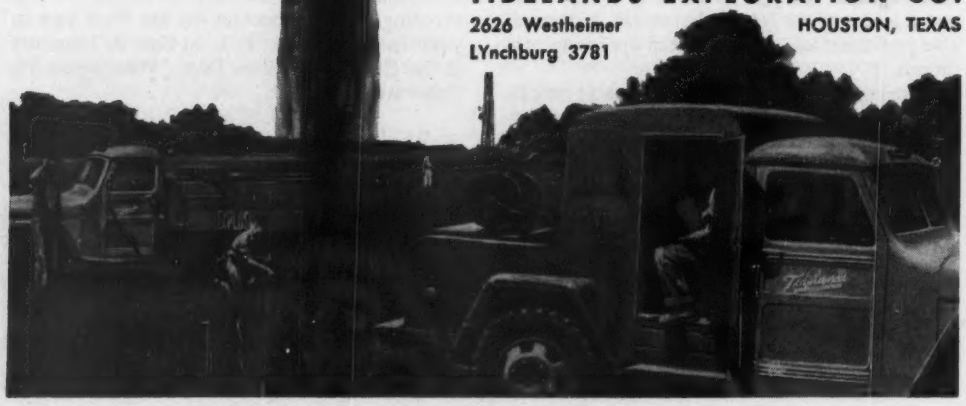

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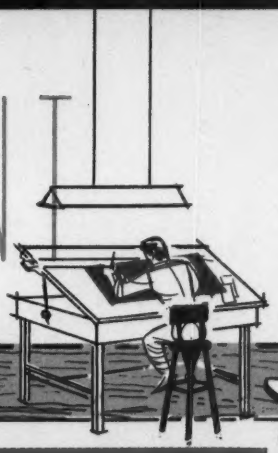

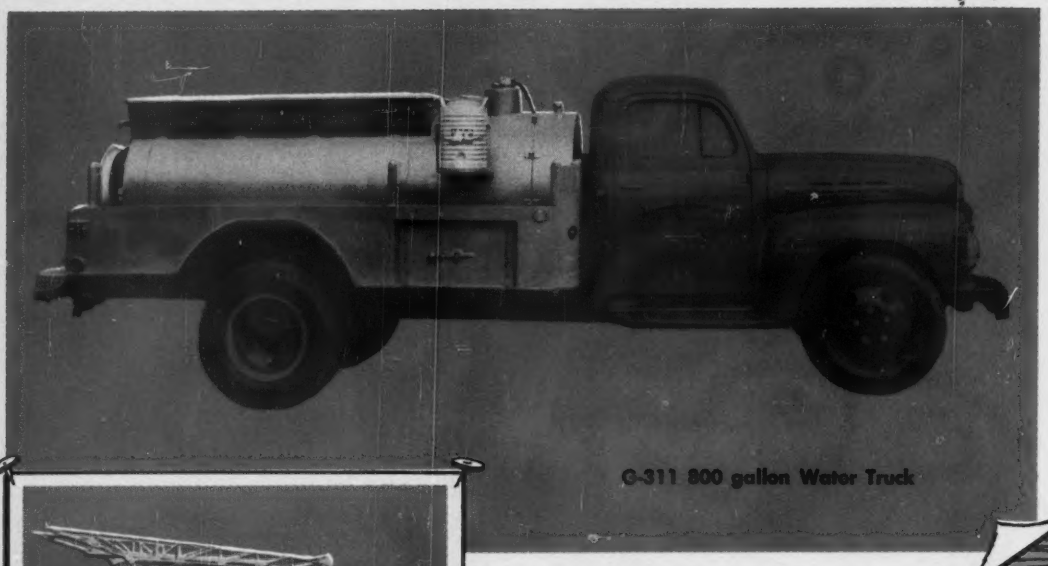

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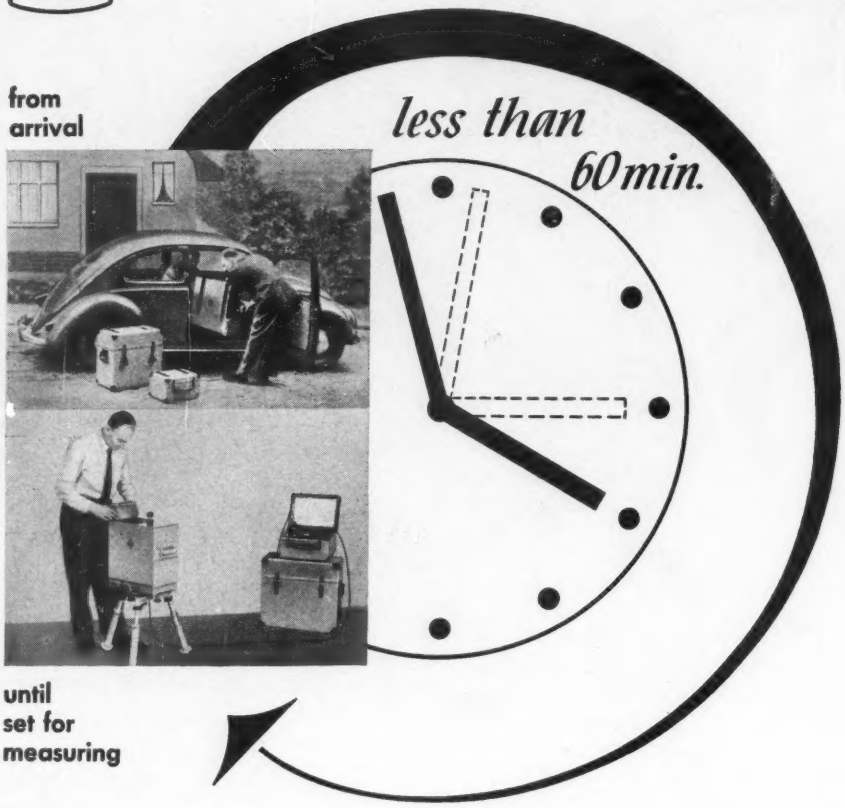

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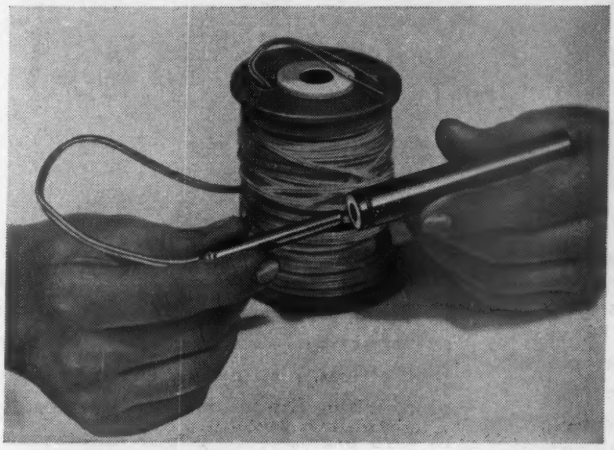

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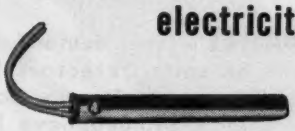

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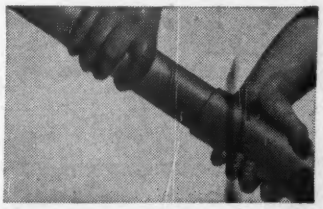

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GEOPHYSICS

TECHNICAL PAPERS

GEOPHYSICAL AND GEOLOGICAL INVESTIGATIONS IN THE GULF OF MEXICO, PART I*

MAURICE EWING†, J. L. WORZEL†, D. B. ERICSON†, AND BRUCE C. HEEZEN†

ABSTRACT

In 1953 the research vessels VEMA and ATLANTIS spent about three weeks in the Gulf of Mexico. Coring, seismic refraction, and topographic studies were undertaken. The topography in the various physiographic provinces is illustrated by reproductions of precision depth records from the continental shelf, continental slope, continental rise, and abyssal plain areas.

Many sediment cores longer than 30 ft were taken in the Gulf. An abrupt change separates approximately three feet of Recent sediments from Wisconsin in all cores taken in depths greater than 1700 fathoms. This change is very similar to one found in many Atlantic and Caribbean cores indicating an abrupt termination of the Wisconsin glacial epoch. Abundant evidence of turbidity current deposition was found in all cores from the abyssal plain and the continental rise. Deposition of sediments in the unusually rough and broad continental slope area is apparently very rapid in the depressions and very slow on the elevations.

The seismic results point to the southern half of the Gulf of Mexico as a typical oceanic area, modified by an increased load of sediments. A profound change near the continental slope is required for connecting this structure to typical continental structures.

INTRODUCTION

In May, 1953 the research vessels ATLANTIS and VEMA spent three weeks making geophysical and geological investigations in the Gulf of Mexico. Special emphasis was placed on refraction seismic measurements, piston coring, and precision echo sounding. The present report is a preliminary interpretation of some of the results.

The PDR (Luskin et al., 1953), a precision depth recorder which allows precision and resolution not obtainable with standard models of depth recorders, was given its first extensive test during this cruise. A resolution of 1 fm in 3,000 fm is possible with this machine. It was built primarily to study abyssal plains like that in the deepest part of the Gulf of Mexico, but it also gave excellent results even on the roughest topography found along the entire track.

The ships entered the Gulf of Mexico through the Yucatan Channel, crossed to Galveston by way of Campeche Bank and the Sigsbee Deep, and then, departed from the Gulf through the Straits of Florida, as shown in Figure 1.

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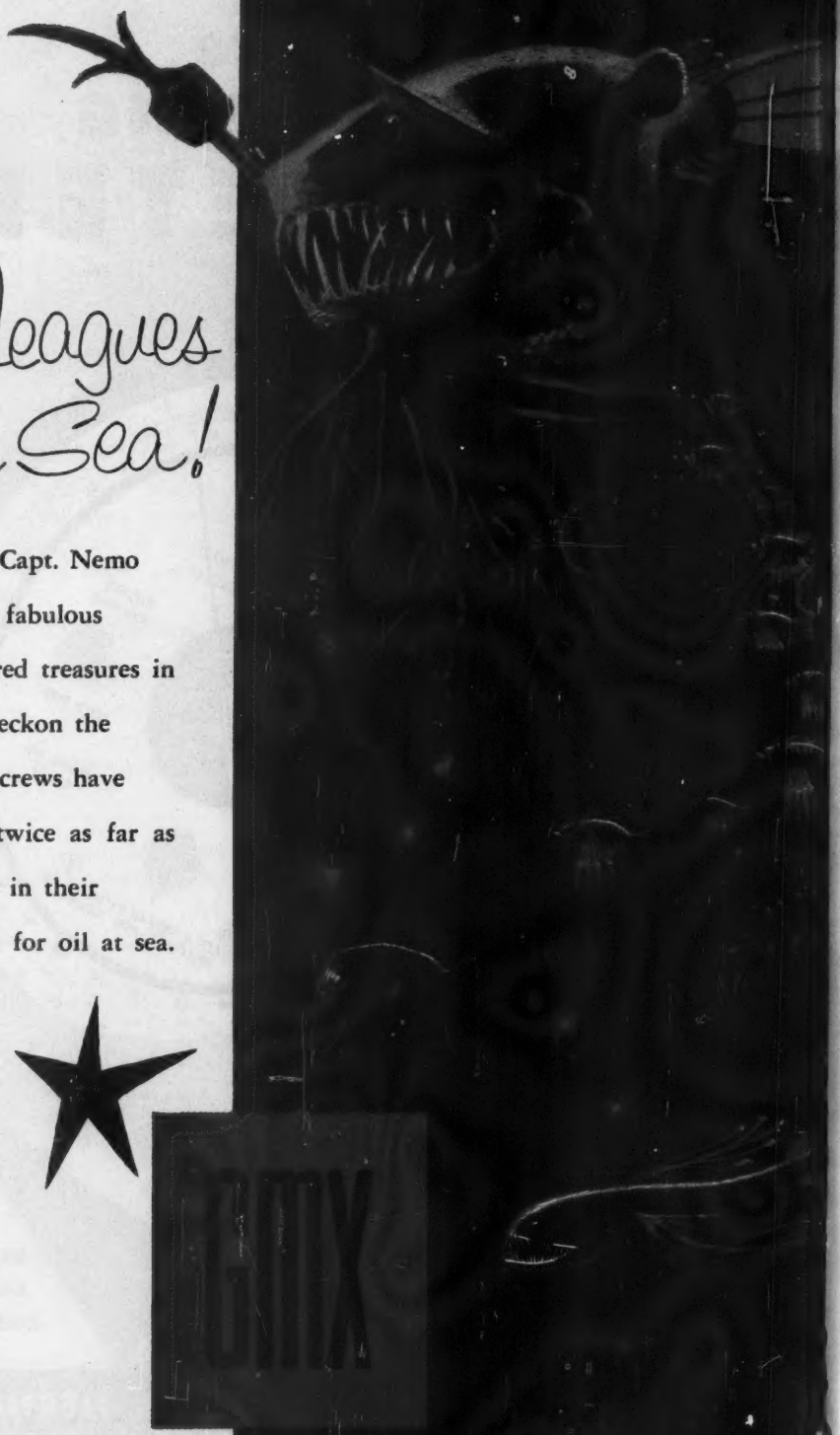

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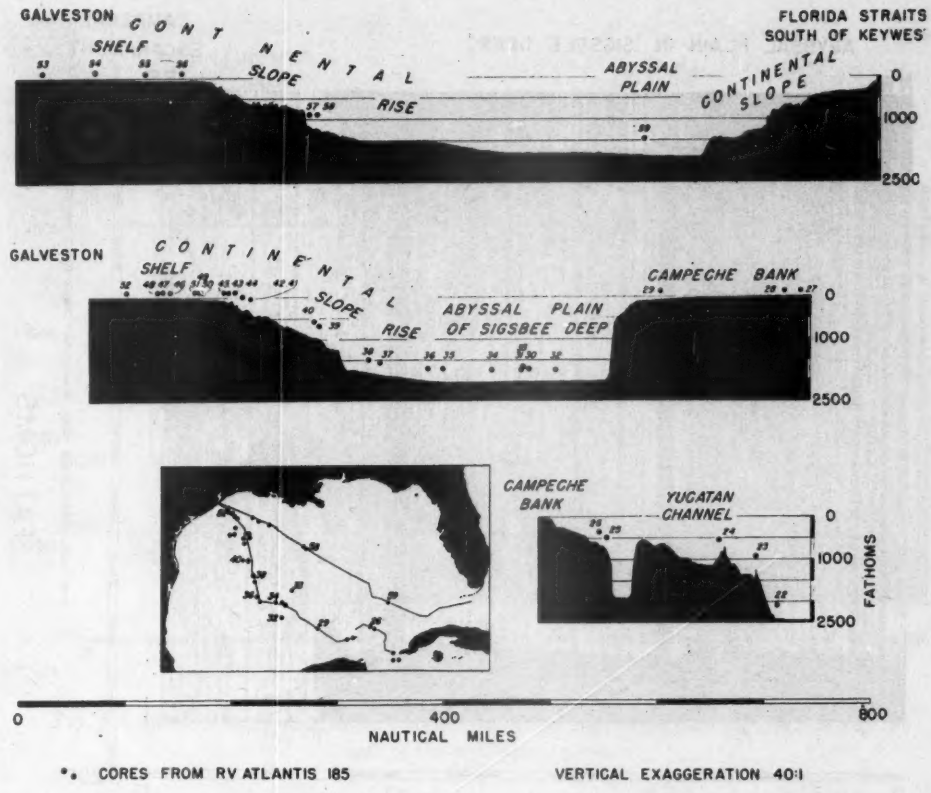

FIG. 2. Three topographic profiles across the Gulf of Mexico.

those in the Bahamas, which Worzel et al. (1953) interpreted as non-tectonic on the basis of gravity data. The flat floor of this trough strongly suggests that it is being filled with turbidity current deposits, probably from a distant northerly source. Paul Weaver (personal communication) has pointed out the possible relation to faults inferred by Alvarez (1954) in the Rio Hondo area on the Mexico-British Honduras boundary.

The Campeche escarpment starts at 600 fm and descends to almost 2,000 fm at the abyssal plain. Figure 3 shows a profile from the foot of this escarpment on to the abyssal plain made up from three consecutive PDR records. Each original PDR record represents 200 fathoms of depth range on an 18-inch scale and progresses at the rate of 12 inches per hour. Near the top of the record opposite the 1,800-fm depth mark is the outgoing signal, from which depths are measured. Near the bottom is the echo from the ocean floor. A suitable multiple of 200 fathoms is always added to this reading. The small trench just off the escarpment is similar to one subsequently found off the Florida escarpment. Its full significance will not be clear until additional data are available.

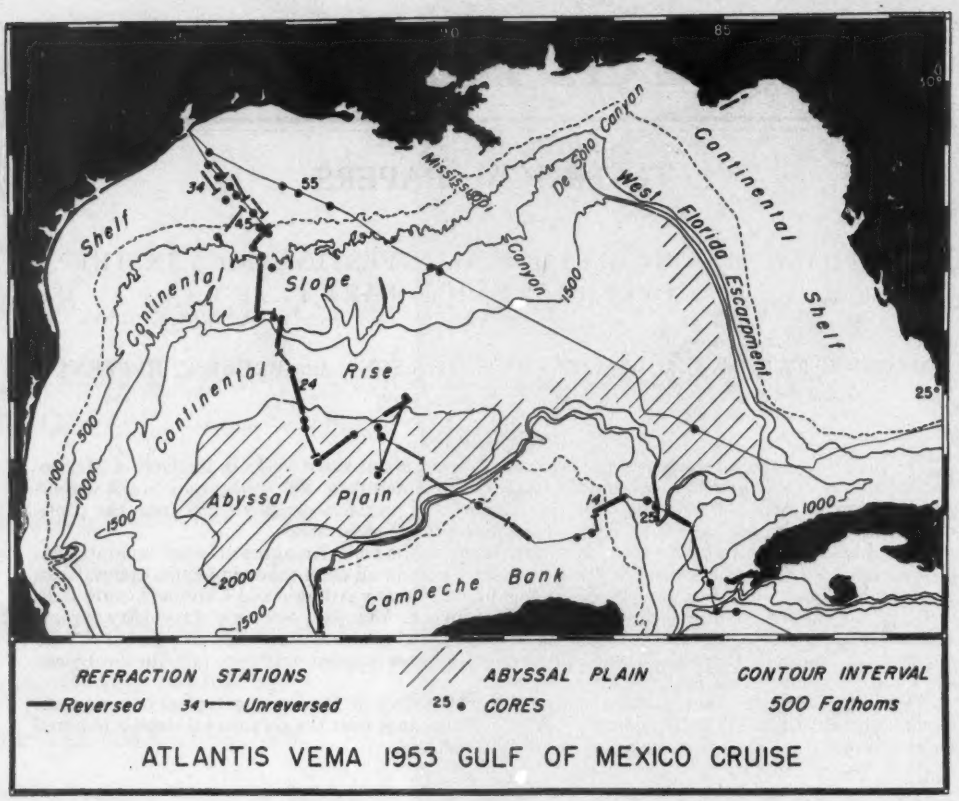

FIG. 1. Base map showing course of cruise, core stations, and refraction lines.

TOPOGRAPHY

The Gulf may be divided into physiographic provinces (Fig. 1) which generally follow those described by Gealy (in press). These are based on morphology, not on absolute depth. They are (1) continental shelves (broad except for Cuba and parts of Mexico); (2) the continental slope including such diverse features as escarpments, broad hummocky areas, and trough areas; (3) the continental rise which is characteristically quite smooth with a very gentle slope; and (4) the abyssal plain. Figure 2 shows three profiles compiled from PDR records. They are drawn with a 40-to-1 vertical exaggeration, and the various physiographic provinces may be readily identified. Note the flat bottom of the trough just east of the location of Core #25 in the northwestern part of the Yucatan Channel. From Figure 1 it may be seen that this is a broad deep valley cutting about 50 miles into the edge of the Campeche Bank. Whether this trough is an erosional or a tectonic feature can only be decided after further evidence is available. There are many points of similarity between the Campeche Bank, the West Florida Shelf, and the Bahamas Platform. This trough is apparently similar to

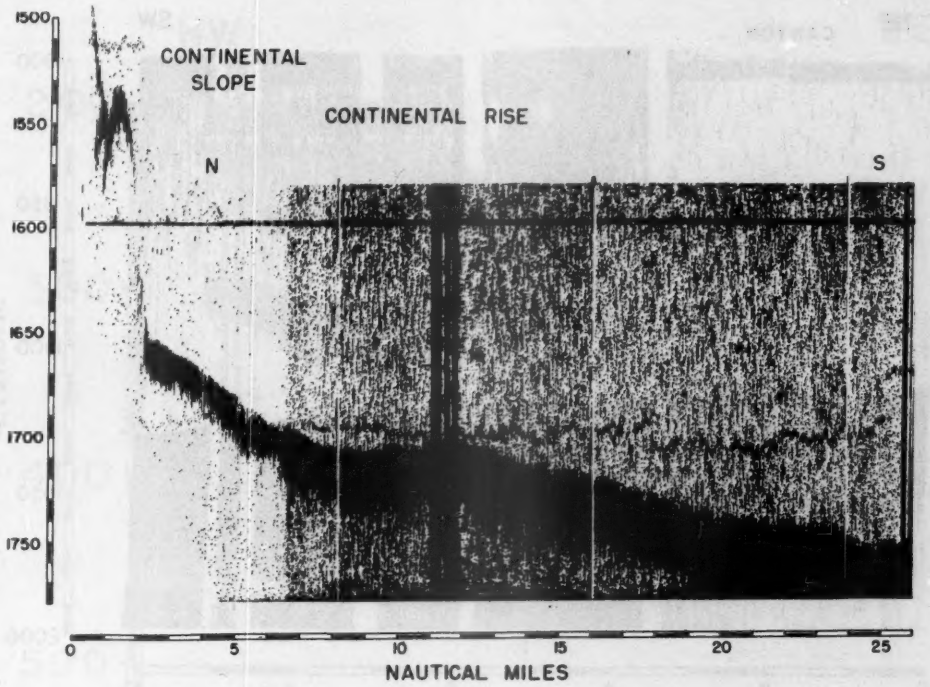

FIG. 5. Cross-section showing upper part of continental rise which joins Sigsbee Scarp at the base of the continental slope.

the base of the continental slope. This scarp runs from a point south of Corpus Christi to the DeSoto Canyon with a possible interruption south of the Mississippi Delta (Gealy, in press; Jordan, 1951). On this profile the scarp drops from 1,300 to 1,650 fathoms. On the crossing from Galveston to the Straits of Florida, the scarp drops from 700 to 1,200 fathoms.

Figure 6 shows a typical section of the continental rise. This area is characterized by a generally smooth bottom which is cut by an occasional small depression. Two or three of these depressions have been crossed so far in our work, but the data are insufficient to show whether they are canyons.

The continental slope, on the other hand, is highly irregular, as shown in Figure 7. Both the topography and the sedimentary studies suggest tectonic activity. The average gradient of this continental slope is 1-to-100, in contrast to the eastern continental slope of the United States where the average gradient is between 1-to-25 and 1-to-40.

Figure 8 shows the edge of the continental shelf on three crossings south of Texas and Louisiana. In the example "South of Galveston" and "South of Morgan City" the break occurs rather sharply and is probably typical of the area. In other cases, as in the example "South of Lake Charles," the break is complicated by the occurrence of a hill.

In Figure 9 hills also appear farther back from the shelf break. It has been long

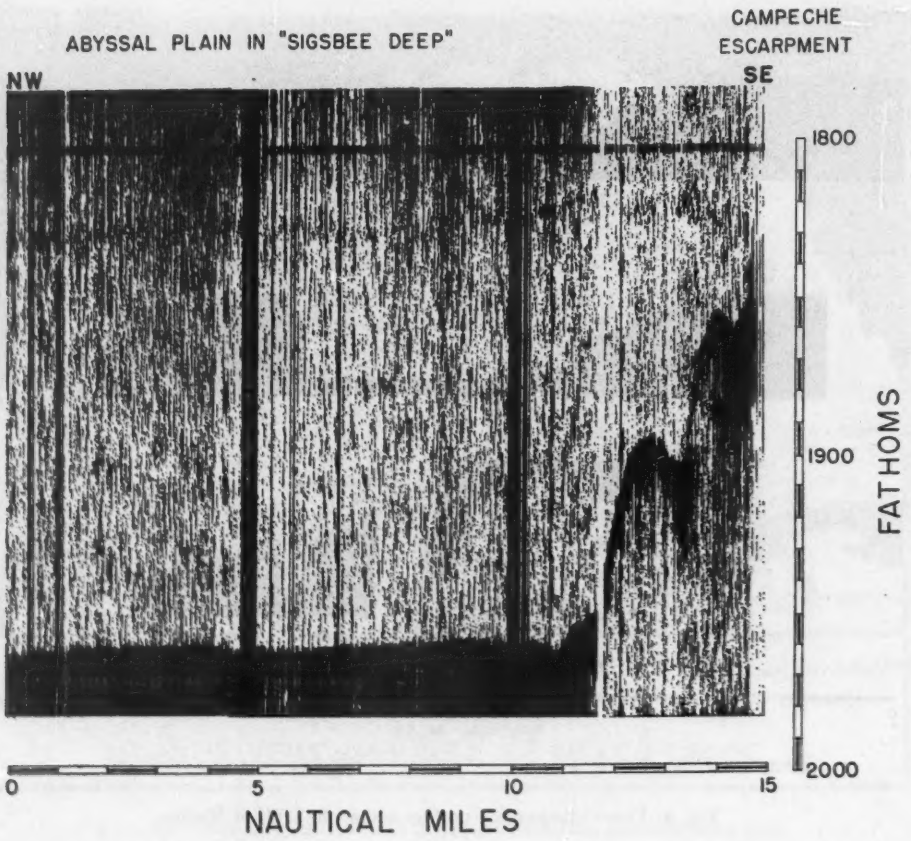

FIG. 3. Fathometer profile from the foot of the Campeche escarpment into the abyssal plain.

The abyssal plain is an extremely flat area, as shown in Figure 4. The gradient here is 1-to-7,000 for a distance of at least 25 miles. This is a typical abyssal plain, its flatness resulting from the sedimentary process which forms the plain.

Figure 5 is a section across the northern edge of the basin. It shows the upper part of the continental rise which joins the Sigsbee Scarp (Gealy, in press) at

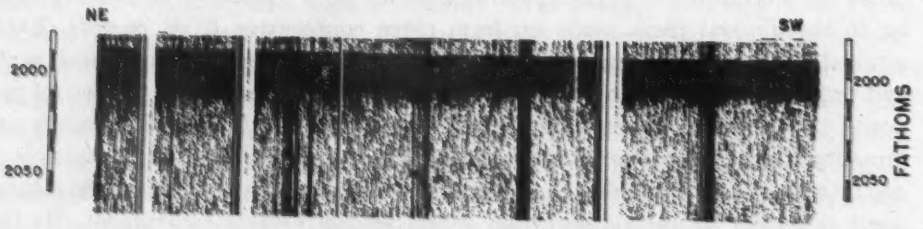

FIG. 4. Topographic profile showing portion of abyssal plain in Sigsbee Deep. Horizontal scale is same as for Figure 5.

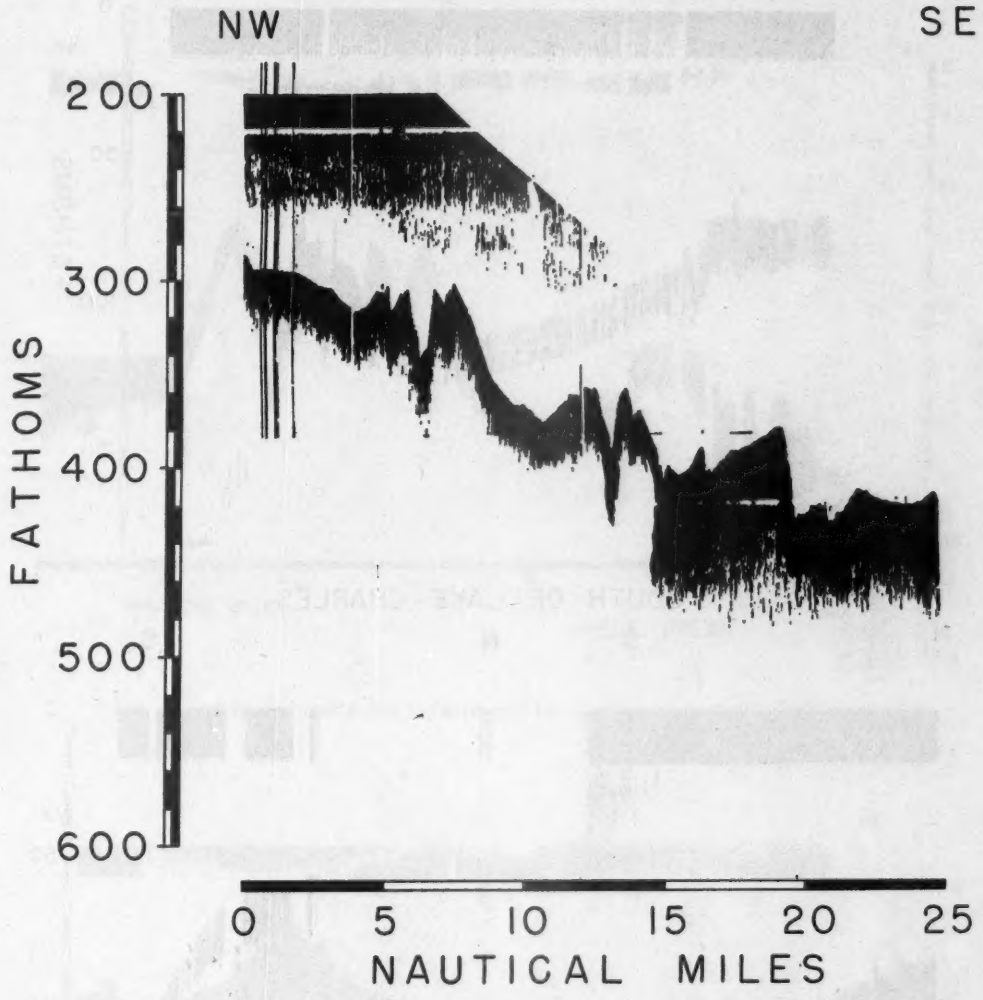

FIG. 7. Cross-section of continental slope south of Lake Charles, La.

taken and handled in such a manner as to preserve the topmost portion of the sediment in an undisturbed condition even when this is almost fluid.

Figure 12 shows the section of cores that we shall discuss. Number 27, the one on the right-hand side, was taken on Campeche Bank in 180 feet (55 m) of water. It is 14 feet long. The top is composed of calcareous muddy sand which becomes coarser toward the bottom. Below about three feet, abundant coral and shell fragments are observed. This change we attribute to eustatic changes of sea level. Two cores on Campeche Bank not shown in the profile are important: Number 25, taken in 5,500 feet (1,690 meters) of water on the wall of the sub-

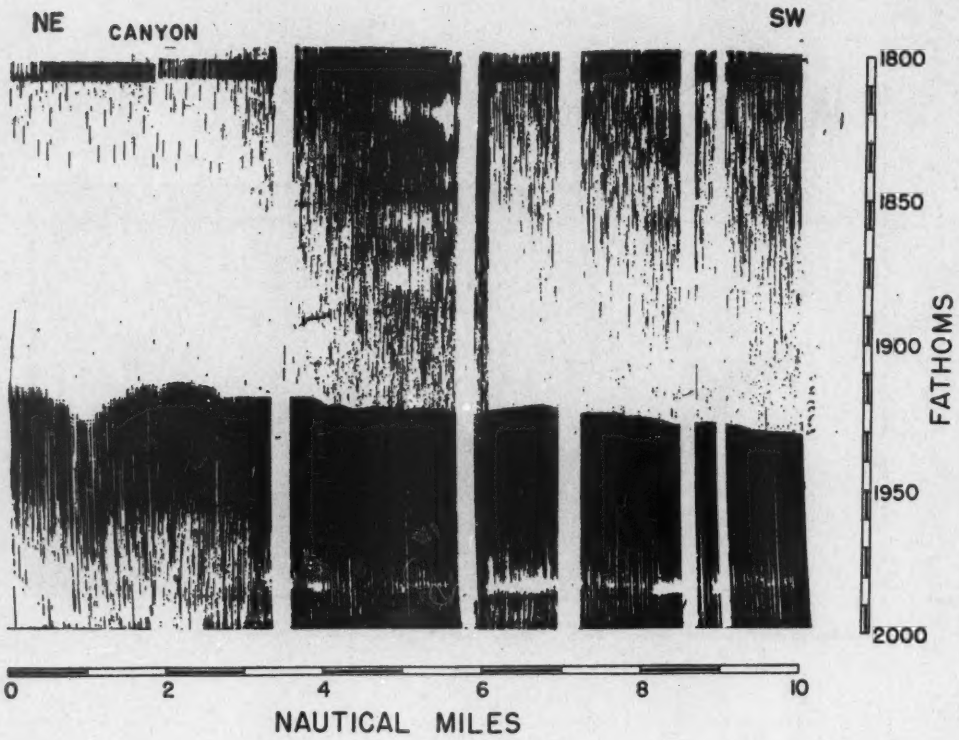

FIG. 6. Topographic profile showing continental rise north of abyssal plain.

known that the outer shelf of the Gulf Coastal Plain is dotted with hills. These have been variously ascribed to salt domes or bioherms or both.

Figure 10 shows one such feature which is interesting for the small protuberances on the side of the hill. These are real, but more evidence is needed to determine their origin. A distinguishing feature of the continental shelf along these profiles is the smoothness of the inner part as compared to the outer part. Some hills on the outer shelf are only a few hundred feet across, while some are a mile or more, as shown in Figure 11.

SEDIMENT CORES

Figure 2 shows the location of the cores with respect to the topography on these courses. We shall discuss only the profile from Campeche to Galveston here; the others still are being studied.

We would like to emphasize that piston corers take undistorted and uncompressed sections. The average length of the cores that we have here is 19 feet, with a maximum of 33 feet. A trigger core is taken within a few feet of each piston core. These trigger cores average about 15 centimeters in length. They are

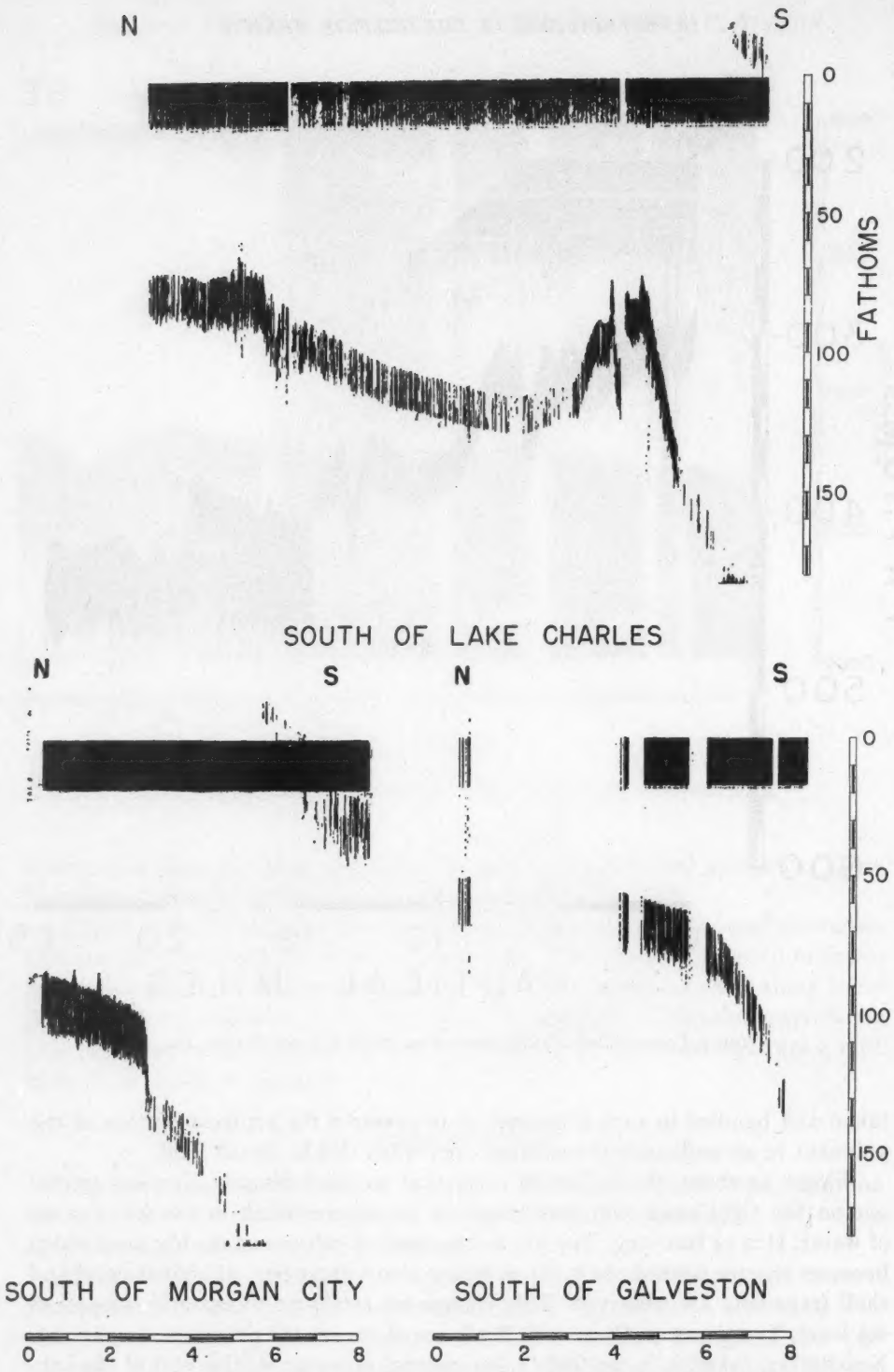

FIG. 8. Fathometer profiles of edge of continental slope off various portions of Texas and Louisiana coasts.

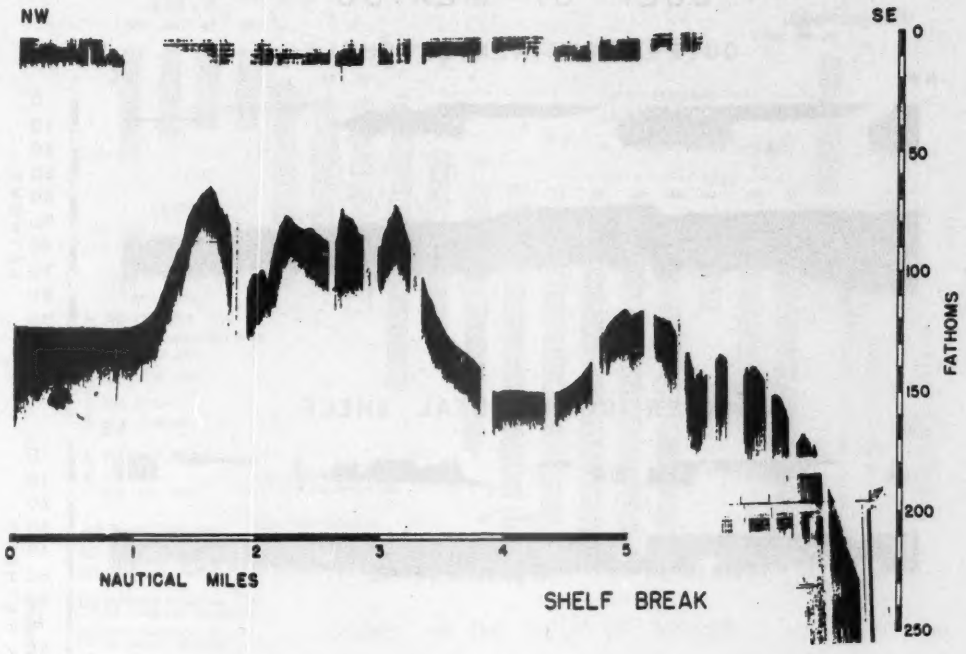

FIG. 9. Fathometer profile showing hills near the shelf break southeast of Galveston.

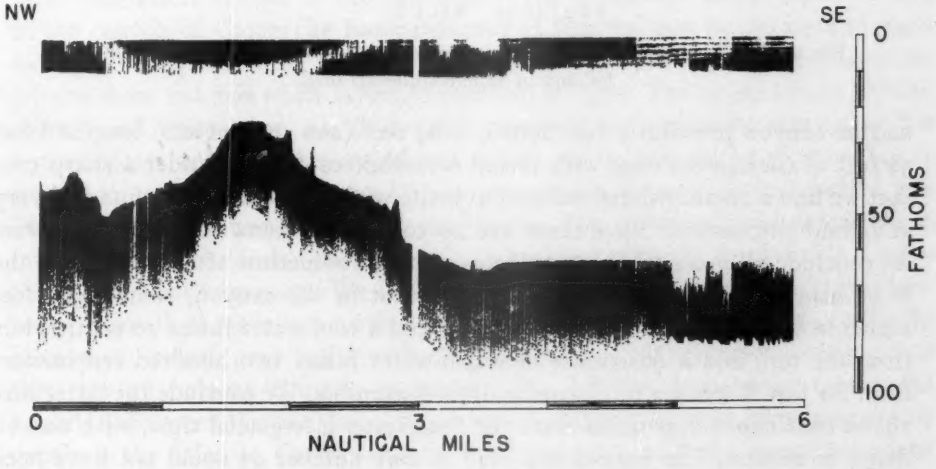

FIG. 10. Fathometer profile showing 28-fathom bank near shelf break southeast of Galveston.

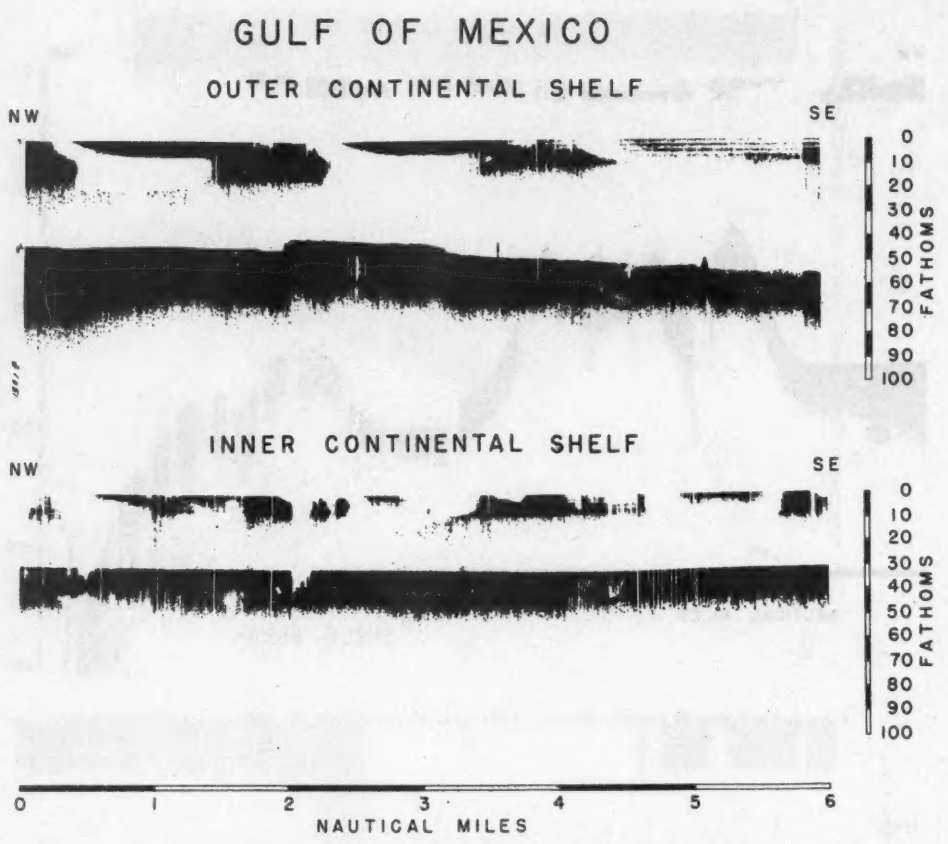

FIG. 11. Profiles showing contrast between smoothness of inner continental shelf and hilliness of outer continental shelf.

marine canyon previously mentioned, is 6½ feet (200 centimeters) long and has 5½ feet of *Globigerina* ooze with recent foraminifera on top. Under a sharp contact we find a cream-colored calcareous lutite with Miocene microfauna and very abundant discoasters. Since there are no cool-water fauna above the Miocene, we conclude all material above this was removed sometime after the close of the Wisconsin. In a nearby core, Number 26, not in the canyon, some 1,500 feet higher in four thousand feet of water, we find a cool-water fauna 20 centimeters from the top, and a recurrence of warm-water fauna two hundred centimeters from the top. There are no discontinuities discernible. We conclude the latter core shows continuous deposition since the Sangamon interglacial time, with no evidence of erosion. The erosion recorded in core number 25 could not have been sub-aerial, since no similar erosional period is evident in core number 26.

Cores 30–35 were in the Sigsbee Deep and in the abyssal plain. The top is composed of a brown foraminiferal lutite 25–40 centimeters thick which contains *Globorotalia menardii* in abundance. This overlies a nearly white calcareous lutite

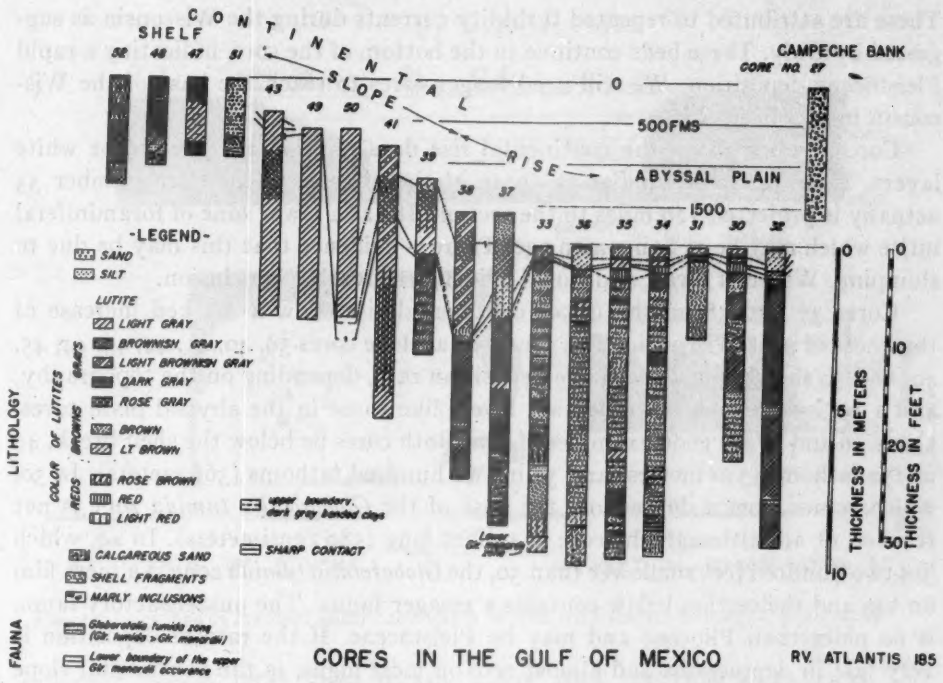

FIG. 12. Sections of typical Gulf of Mexico cores from various physiographic provinces.

with foraminifera similar to those of the top section. The nearly white lutite contains discoasters similar to the Miocene of the Campeche Bank. Thus we find in the canyon of Campeche Bank evidence of removal and in the abyssal plain evidence of deposition of a similar material. For several reasons we cannot attribute these red and white layers to climatic changes. The upper halves of both the red and white layers are thoroughly reworked by burrowing organisms; the bottom parts are not. One would not expect sharp boundaries if these layers were due to climatic changes. Discoasters, which became extinct before the Pleistocene, are abundant in the white layers. The white-over-red succession is found nowhere else in our more than four hundred cores in the Atlantic, Caribbean, and Mediterranean. We conclude these layers are due to turbidity currents. Beneath these layers we find a brown foraminiferal lutite which gradually changes to a dark gray lutite with silty layers and microfauna so meager that they are no help as climatic indicators. We believe this change marks the boundary between the last glacial stage and the Recent. In cores from comparable depths in the Atlantic, Caribbean, and Mediterranean, we find a faunal boundary between warm-water species and cold-water species at a comparable position in the cores (if we neglect the red and white layers). This indicates a rather fundamental climatic change at the end of the last glacial period. The interbedded silt layers show excellent graded bedding typical of turbidity current deposition.

These are attributed to repeated turbidity currents during the Wisconsin as suggested by Daly. These beds continue to the bottom of the core, indicating a rapid Pleistocene deposition. We will need longer cores to reach the base of the Wisconsin in this basin.

Core number 36 on the continental rise does not contain the red or white layers. It is otherwise similar to those of the abyssal plain. Core number 33 actually is projected 120 miles to the section. It has a lower zone of foraminiferal lutite which may be of Sangamon age. There is evidence that this may be due to slumping. We must await additional evidence to reach a conclusion.

Cores 37 and 38 on the upper continental rise show a marked increase of thickness of post-Wisconsin. The continental slope cores 39, 40, 41, 42, 43, 44, 45, 49, and 50 show a highly variable deposition rate, depending on the topography, and a noticeable lack of graded silt layers like those in the abyssal plain cores. Cores 49 and 50 are good examples of this. Both cores lie below the shelf break, 49 in 170 fathoms (310 meters) and 50 in two hundred fathoms (366 meters). In 50, which comes from a depression, the base of the *Globorotalia tumida* zone is not reached at all, although the core is 19 feet long (580 centimeters). In 49, which lies two hundred feet shallower than 50, the *Globorotalia tumida* zone is a mere film on top and the section below contains a meager fauna. The unsatisfactory fauna is no older than Pliocene and may be Pleistocene. If the rate of deposition is very fast in depressions and almost zero on local highs, as the continental slope cores seem to indicate, the original bottom irregularities ought to have been smoothed out to a considerable extent. Instead, the continental slope south of Galveston has an unusually large number of local highs and lows. It is hard to avoid the conclusion that there has been much local rather small-scale tectonics here in the Pleistocene and perhaps even in Recent time. Therefore we conclude: (1) Campeche Bank is calcareous and biogenic, differing largely from the abyssal plain, continental rise, and continental slope, which are clastic and minerogenous; (2) the abyssal plain cores show abundant evidence of turbidity-current deposition. In spite of this the deposition in recent times has not been excessive. On the other hand deposition during the Wisconsin glacial stage seems to have been very largely by turbidity currents and the rate of deposition was correspondingly rapid; (3) deposition on the continental slope and rise has been variable, largely dependent on topography, fast in the depressions, slow on the elevations; (4) Miocene calcareous lutite was reached in the canyon on Campeche Bank; (5) two or three cores on the continental slope may have reached the Pliocene.

SEISMIC REFRACTION MEASUREMENTS

Figure 13 shows the seismic refraction stations in relation to the topography. Calculations have been completed for only six stations.

Figure 14 shows records from refraction shooting. Note that the records have been folded at a point near the left-hand side of the illustration. Profile

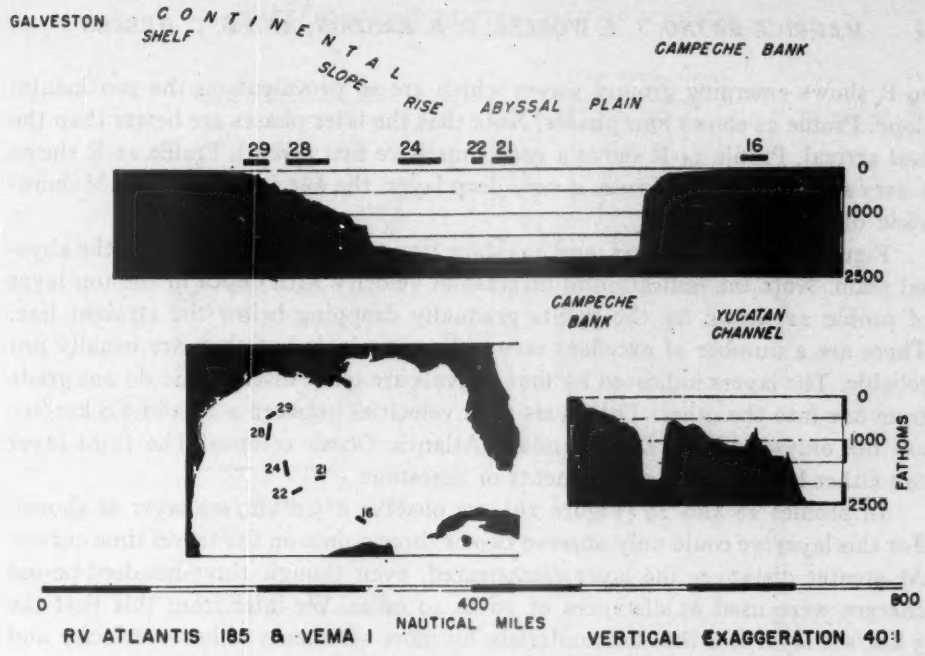

FIG. 13. Locations of reversed seismic refraction profiles with respect to bottom topography.

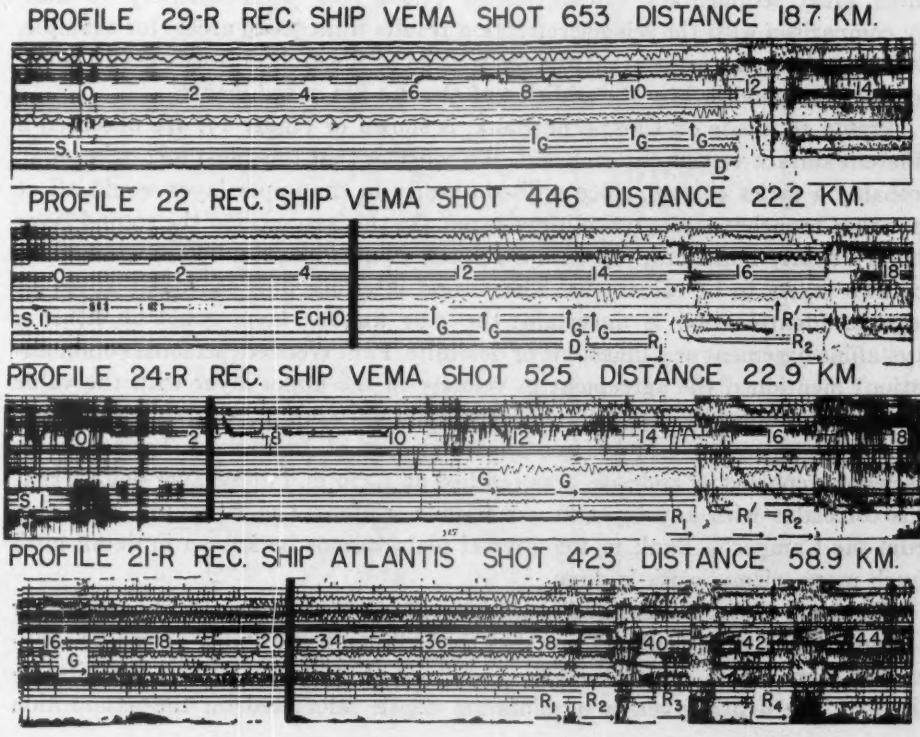

FIG. 14. Some typical seismic refraction records made in the Gulf of Mexico.

29-R shows emerging ground waves which are so prevalent on the continental slope. Profile 22 shows four phases. Note that the later phases are better than the first arrival. Profile 24-R shows a good impulsive first arrival. Profile 21-R shows a very sharp first arrival from a very deep layer, the one just above the Mohorovicic discontinuity.

Figure 15 (Profiles 21, 22, and 24) show typical travel time curves in the abyssal plain. Note the indication of increase of velocity with depth in the top layer of profile 22 shown by the points gradually dropping below the straight line. There are a number of excellent second-layer arrivals but they are usually not reliable. The layers indicated by first arrivals are quite distinct and do not grade from one into the other. The layers with velocities between 2.25 and 6.0 km/sec are the only additions to a standard Atlantic Ocean column. The third layer can either be consolidated sediments or limestone.

In profiles 28 and 29 (Figure 16), we observe a 5.0 km/sec layer as shown. For this layer we could only observe two or three points on the travel time curves. At greater distances the layer disappeared, even though three-hundred-pound charges were used at distances of 20 to 40 miles. We infer from this that the 5 km/sec layer is a thin bed underlain by more sediments of lower velocity and unknown thickness. This thin bed may be interpreted to be either a limestone layer or a salt layer. Just inshore of these stations, field plots indicate basement under great sedimentary thicknesses of 35,000 feet (approximately 10 km). By comparison with the seismic refraction results from ocean areas (for example, Ewing et al., 1954) we see that the main basin of the Gulf of Mexico is a typical oceanic area, modified by the addition of about 7 km of sediments.

Profile 16, made on Campeche Bank, is shown in Figure 17. We observed a different surface velocity at each end. We consider that this must be gradational, probably a facies change, since a discontinuity in the upper layer would affect the other branches of the travel-time curve. On this assumption the second layer shows a nearly horizontal top with a velocity of 4.82 km/sec. We consider these top two layers to be calcareous. The second interface dips southeast about 1½ degrees. Identification is uncertain; the 5.67 km/sec layer could be either a crystalline basement or a limestone or dolomite. Paul Weaver (personal communication) mentioned the agreement in velocity in the upper layer with the value 2.41 km/sec found by logging a well near Merida (Cué A., 1953). The interval velocity increased to 3.65 km/sec at 850 m (top of Paleocene). Igneous rock, elsewhere reported as andesite, was reached at 1,270 m, but Weaver doubts that this correlates with any layer in our seismic section. The structural transition from the Campeche Bank to the abyssal plain cannot be known in detail until much more seismic work is done.

Figure 18 shows a seismic section across the Gulf of Mexico. Stations number 21 and number 22 are alike except that the sediments at number 21 can be broken into more layers. On station 21 we did not observe the Mohorovicic discontinuity. The depth given is a minimum depth calculated on the assumption

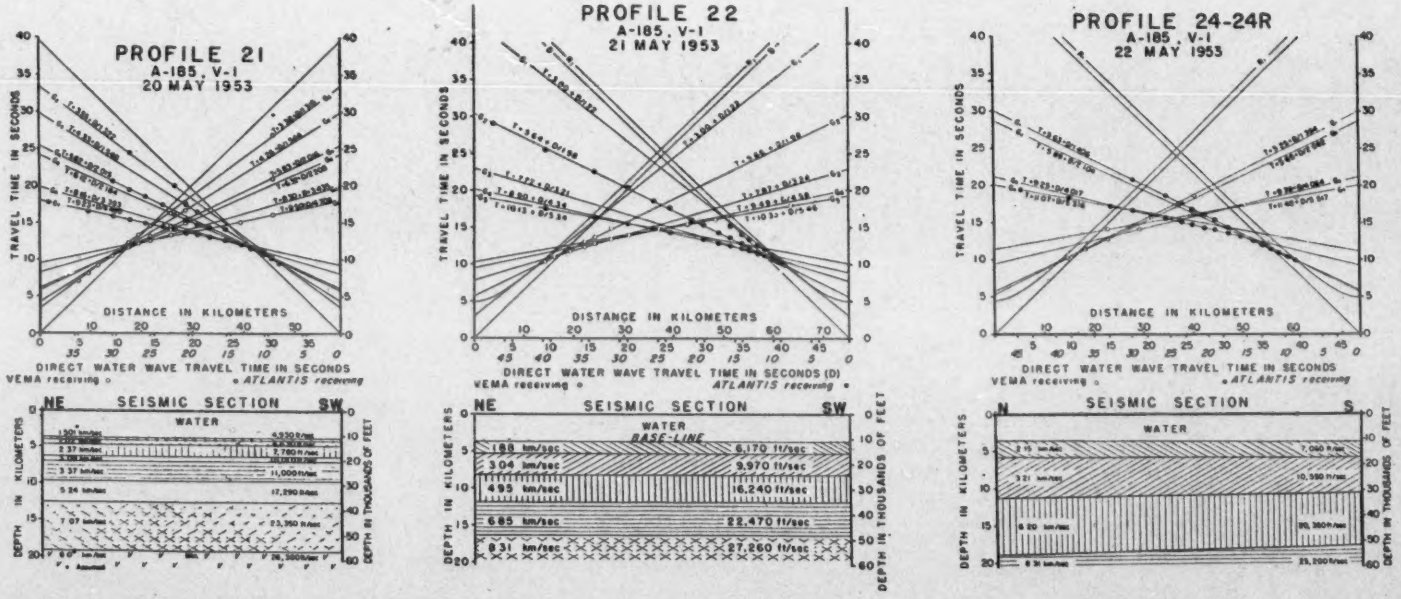

FIG. 15. Typical travel-time curves and cross sections from three reversed refraction profiles in the abyssal plain.

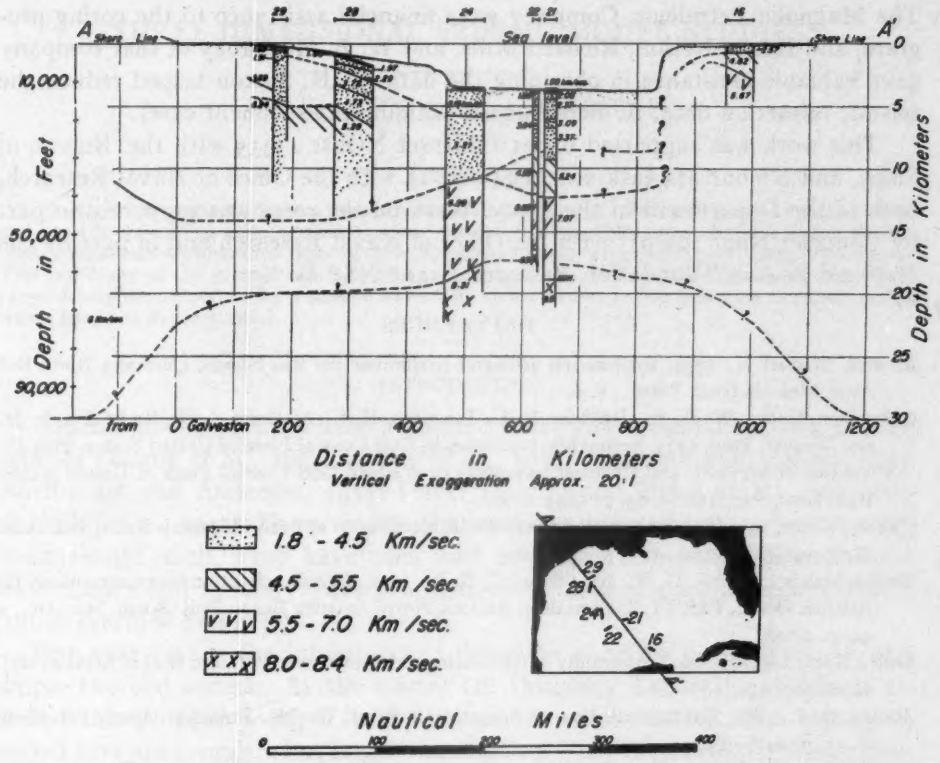

FIG. 18. Composite seismic structure section along profiles on line crossing the Gulf from Galveston to Yucatan Peninsula.

that the Mohorovicic discontinuity would have been observed at a slightly greater shot distance. On station 24 we did not observe the 5.0 km/sec layer, possibly because of the shot spacing. If we put it in with the maximum possible thickness, the 3.22 km sedimentary layer is 1 km shallower, the 5.0 km/sec layer is 2½ km thick, and the Mohorovicic discontinuity is ½ km deeper.

Colle et al. (1952) give the sedimentary base at 45,000 feet (ca. 14 km) at the Texas coast of the Gulf. Nettleton (1952) shows the regional dips of the sedimentary layers from geophysical evidence. The consensus among most earthquake seismologists is that the Mohorovicic discontinuity lies at a depth of about 30 km beneath the continents. Although earthquake data are not available for the structure beneath Texas, it is probable that this number would be approximately correct. We have included this in our section of Figure 18 for comparison purposes.

ACKNOWLEDGMENTS

We wish to express our deep thanks for assistance in the field to the officers and crew of the ships and to the many people who assisted in obtaining the data.

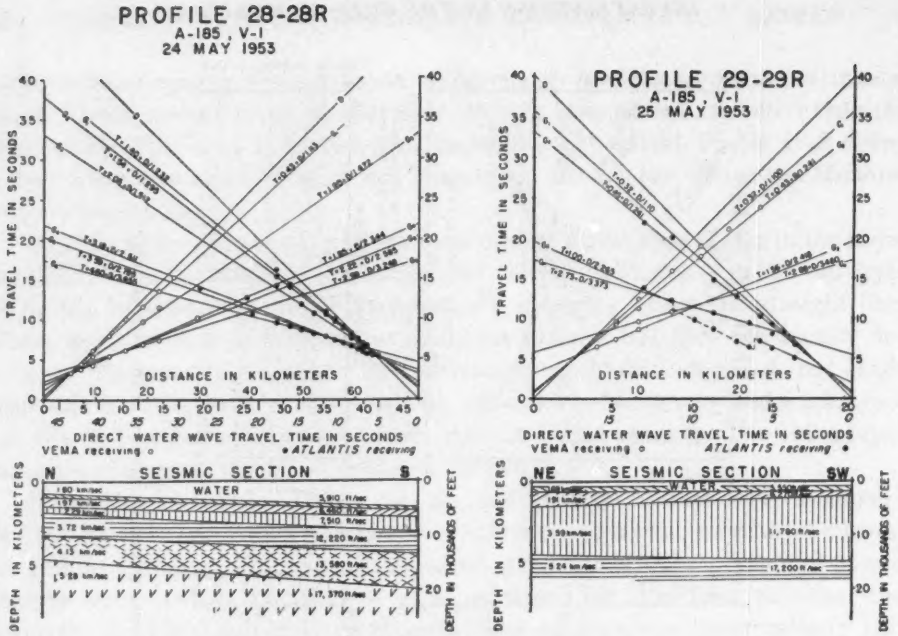

FIG. 16. Refraction travel-time curves and cross-sections from two profiles indicating presence of a layer with a speed slightly greater than 5 km/sec.

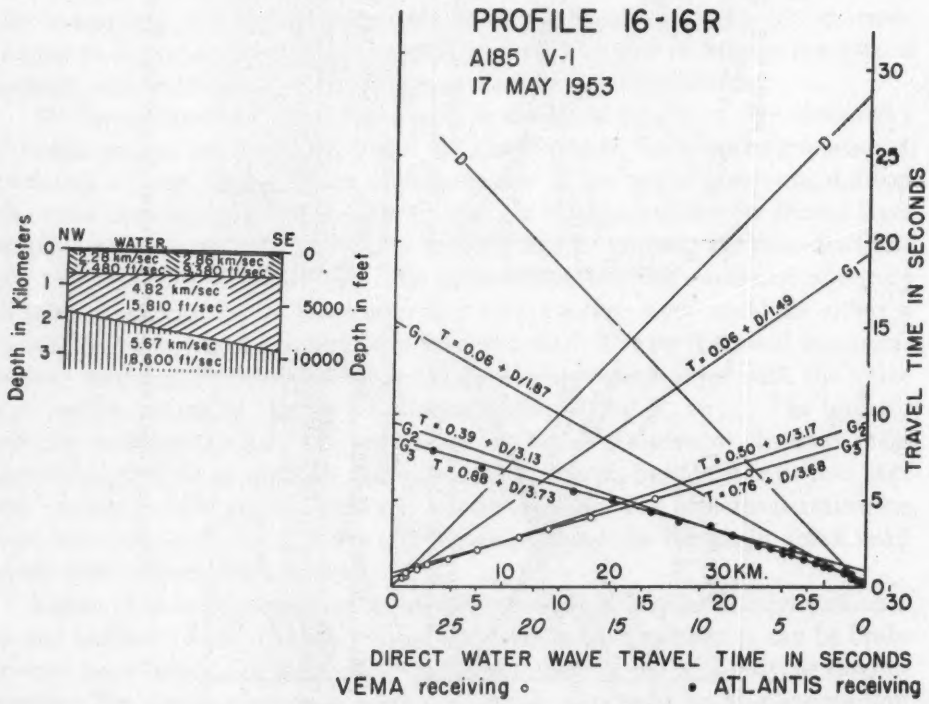

FIG. 17. Refraction travel-time curves and cross-section for profile 16-16R over Campeche Bank.

GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 19–32, 13 FIGS.

THREE-DIMENSIONAL SEISMIC MODEL STUDIES*

F. K. LEVIN† AND H. C. HIBBARD†

ABSTRACT

Elastic wave propagation in a two-layer section has been studied with a solid two-bed model and records resembling seismograms obtained for the four possible source-detector configurations. Numerous events are identified. Among these, the shear waves are found to be surprisingly prominent. The amplitude of the ground roll falls off approximately as (distance)$^{-1/2}$. This is the amplitude-range dependence expected for a surface wave. The ability of two in-line detectors to reduce surface waves has been demonstrated.

INTRODUCTION

Seismic models recently have been described by investigators at several laboratories (Evans et al., 1954; Howes et al., 1953; Kaufman and Roever, 1951; Northwood and Anderson, 1953; Oliver et al., 1954; Press et al., 1954; Riznichenko et al., 1951). These models represent on a reduced scale pulses traveling in an elastic earth. They have been used to confirm the predictions of elastic wave theory and to study wave propagation in cases where mathematical difficulties preclude prediction.

One such case is the initiation and detection of pulses on the surfaces of a simple two-bed section. At the Carter Oil Company Laboratory we have attacked this problem using a three-dimensional seismic model. The results reported here are complete but largely qualitative. They are at present being compared with theory.

THE TWO-BED MODEL

The two-bed model consists of a three inch thick slab of Sauereisen No. 31 cement over a one inch thick slab of marble. On the chosen scale of one foot of model to a thousand feet of earth, the cement represents 250 feet of shale or sandstone; the marble, 83 feet of limestone. Relevant physical properties are summarized in Table I.

TABLE I

Model Material	Specific Gravity	Dilatational Wave Velocity
Cement	2.0	7,300 ft/sec
Marble	2.7	18,400 ft/sec

Model pulse frequencies lie in the range of 10 to 100 kc/sec, corresponding to seismic frequencies of 10 to 100 cps. The equipment and techniques of ultrasonic pulse generation and detection in the model are described in the Appendix.

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The Magnolia Petroleum Company gave financial assistance to the coring program, and Henry Nelson, Richard Mills, and W. B. Huckabay of that company gave valuable assistance in obtaining the data. G. H. Sutton helped reduce the seismic refraction data. A. Bally helped examine the sediment cores.

This work was supported under Contract NObsr 43355 with the Bureau of Ships, and N6 onr 271 task orders 24 and 13 with the Office of Naval Research, both of the Department of the Navy. Work on the cores was supported in part by Contract Nonr 266(01) with the Office of Naval Research and in part by the National Science Foundation Research Grant NSF-G 763.

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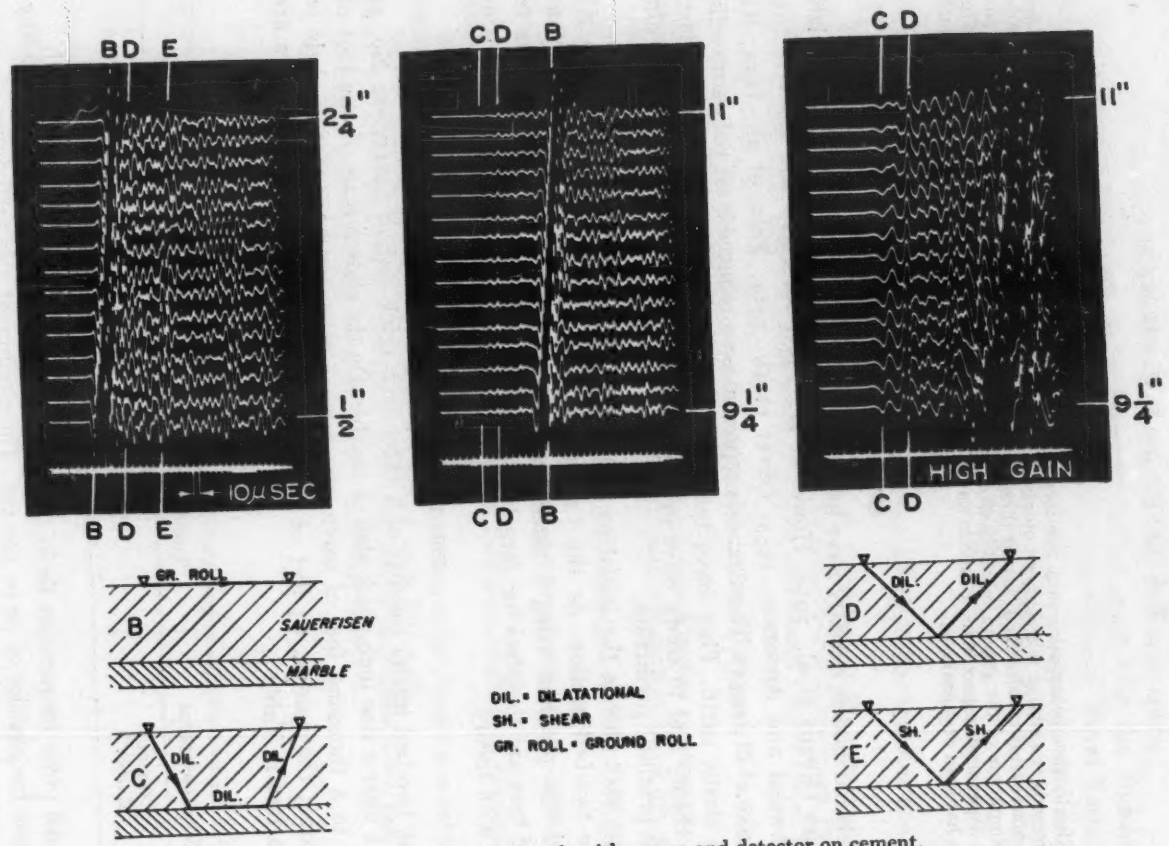

FIG. 1. Typical model records with source and detector on cement.

RESULTS

Seismograms will be shown for all four source-detector configurations possible with a two-bed model. Typical records taken with the source and detector both on the cement appear in Figure 1. The equivalent geophone separation on the earth is 10 feet and the equivalent pulse breadth is 11 milliseconds. At small source-detector separations, the large-amplitude ground roll completely hides the initial arrival but for greater distances, low-amplitude dilatational events are visible. In the usual notation, the events identified in Figure 1 are the direct ground roll arrival, the P_1P_1 and S_1S_1 reflections, and the $P_1P_2P_1$ refraction.[1]

By placing the source and detector on the marble surface, we have simulated operations over an area characterized by a high-speed surface bed (Fig. 2). In this work, the equivalent pulse breadth is six milliseconds. The records obtained here differ from those on the cement in several ways. The amplitude of the direct dilatational arrival P_2 decreases so rapidly with distance that it is nearly undetectable at 11 inches. No dilatational reflections can be identified with certainty and events traveling with the shear velocity of the marble are prominent. Finally, the second largest event on the record appears to be the shear-dilatational-shear conversions $S_2P_1S_1S_2$ and $S_2S_1P_1S_2$. Other events on Figure 2 include the direct ground roll and the shear reflection $S_2S_1S_1S_2$.

No change of pulse breadth occurs along the record either for the profiles taken along the marble or for those on the cement. We attribute this in part to the technique of pulse shaping at the source and to wave lengths small compared to the bed thickness. In addition, the model has no low-velocity layer. Since all events have about the same frequency characteristics, filtering to eliminate ground roll is impractical.

Except in relatively few studies carried out with deep geophones locked in wells, the down-traveling pulses are not recorded in exploration seismology and the nature of these pulses must be inferred from reflected events detected with surface spreads. Pulses transmitted through the model, on the other hand, may be recorded. Figure 3 shows sample seismograms taken with the source on the cement and detector on the marble. In Figure 4, the source and detector are interchanged. The equivalent geophone separation is 10.4 feet. The directly transmitted shear event S_1S_2 is not apparent when the source and detector are opposite one another but appears suddenly at greater distance. Still further along the profiles, a converted dilatational-shear wave P_1S_2 separates out and continues parallel to S_1S_2. The large amplitude of these two events explains the prominence of event *D* of Figure 2 ($S_2P_1S_1S_2$ and $S_2S_1P_1S_2$). At large distances, the direct arrival P_1P_2 becomes negligibly small. In general, the region of maximum energy shifts toward later times with increasing source-detector separation.

Although the seismograms of Figures 3 and 4 are different in appearance, the same events—P_1P_2, P_1S_2, and S_1S_2—are prominent in both figures. In the ab-

[1] The abbreviation SH for shear wave in Figure 1 and subsequent figures is unfortunate. In the usual notation, the events are actually SV waves.

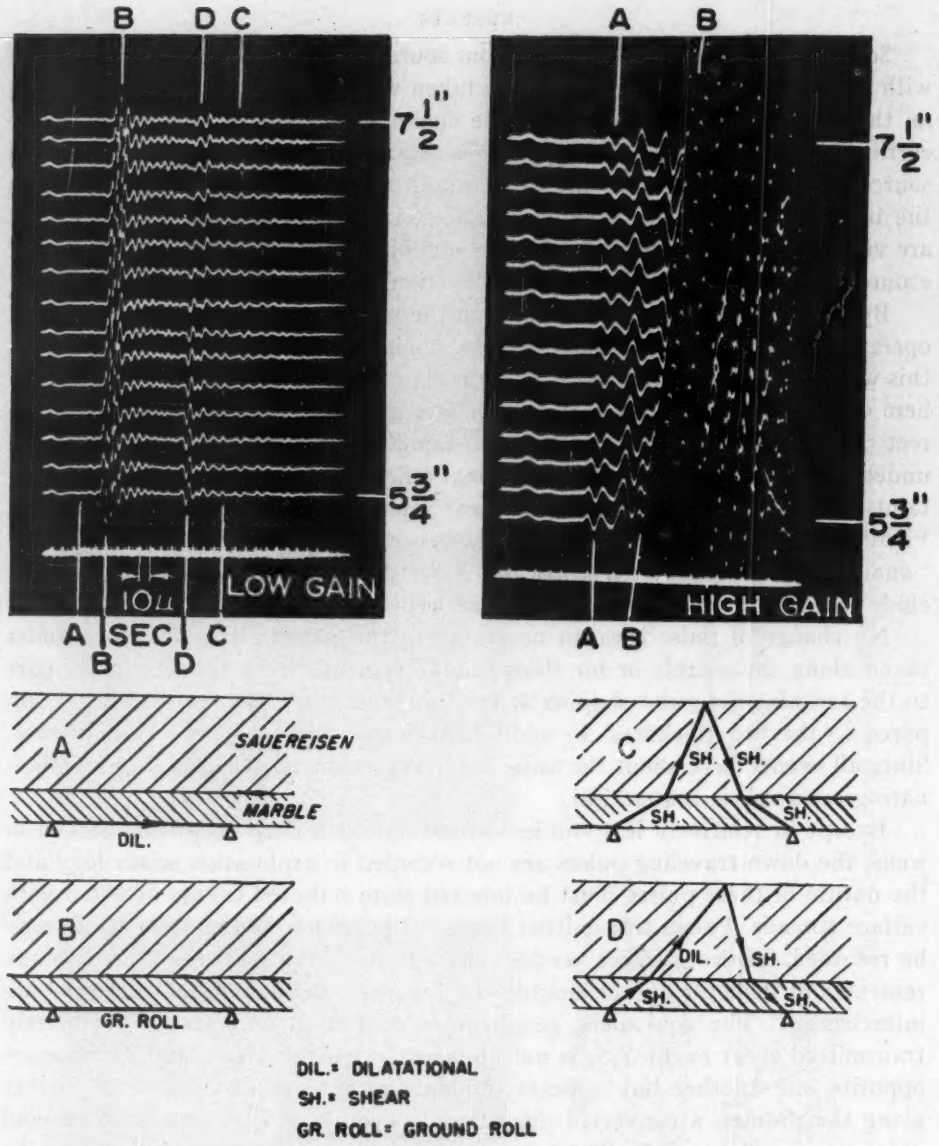

FIG. 2. Typical model records with source and detector on marble.

sence of a satisfactory theory for two-layer model amplitudes, we offer no explanation for this observation.

Quantitative data of two types are obtained with the two-bed seismic model: travel times and amplitudes of selected events. The times of every peak and valley for events arriving within 250 microseconds of pulse initiation have been

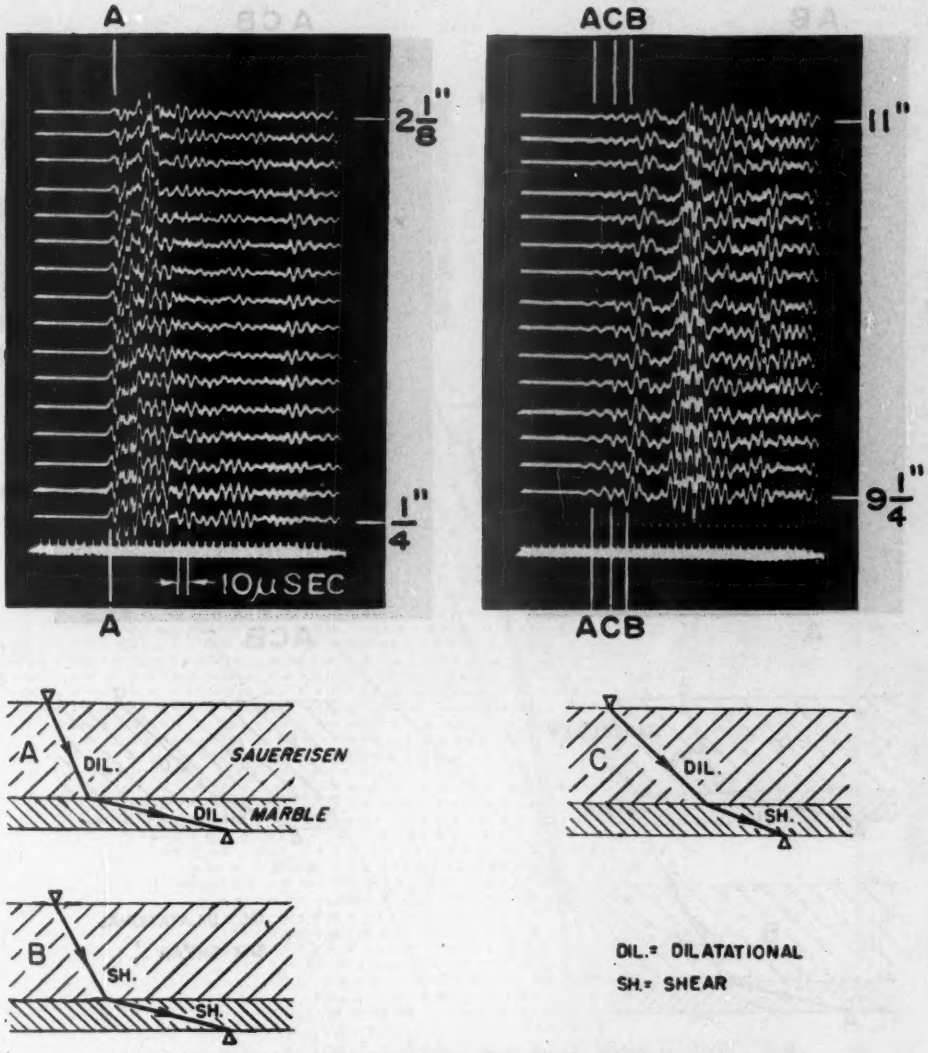

FIG. 3. Typical model records with source on cement, detector on marble.

plotted against horizontal distance and theoretical time-distance curves, superimposed on the experimental points. Figures 5 to 8 are such plots for the four configurations. In general, the agreement of theory and experiment is satisfactory. As mentioned previously, the pulses are shaped before being applied to the input transducer and all theoretical curves have been displaced to correct for the time zero.

While absolute travel times can be determined accurately, we have measured only relative amplitudes and those with great difficulty. By noting the sig-

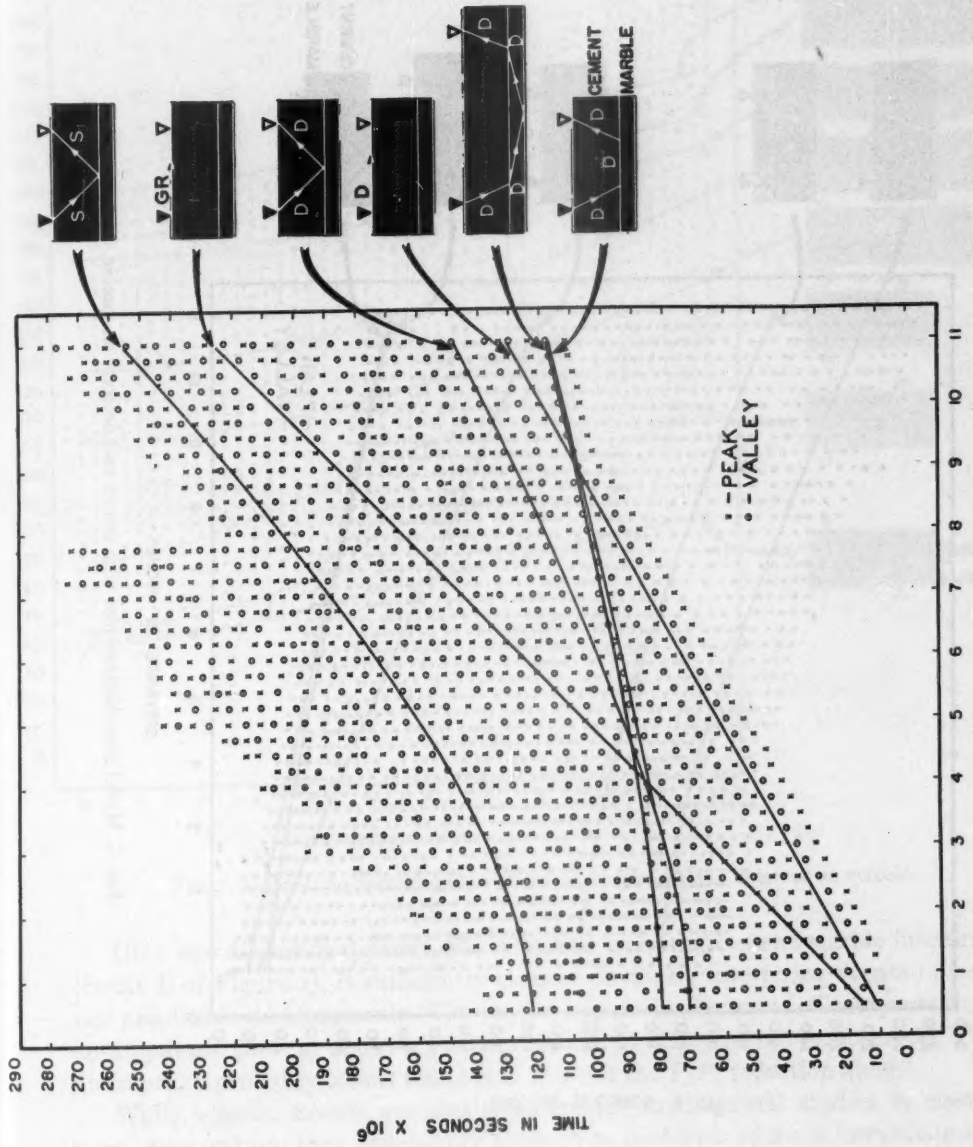

FIG. 5. Model time-distance plot with source and detector on cement.

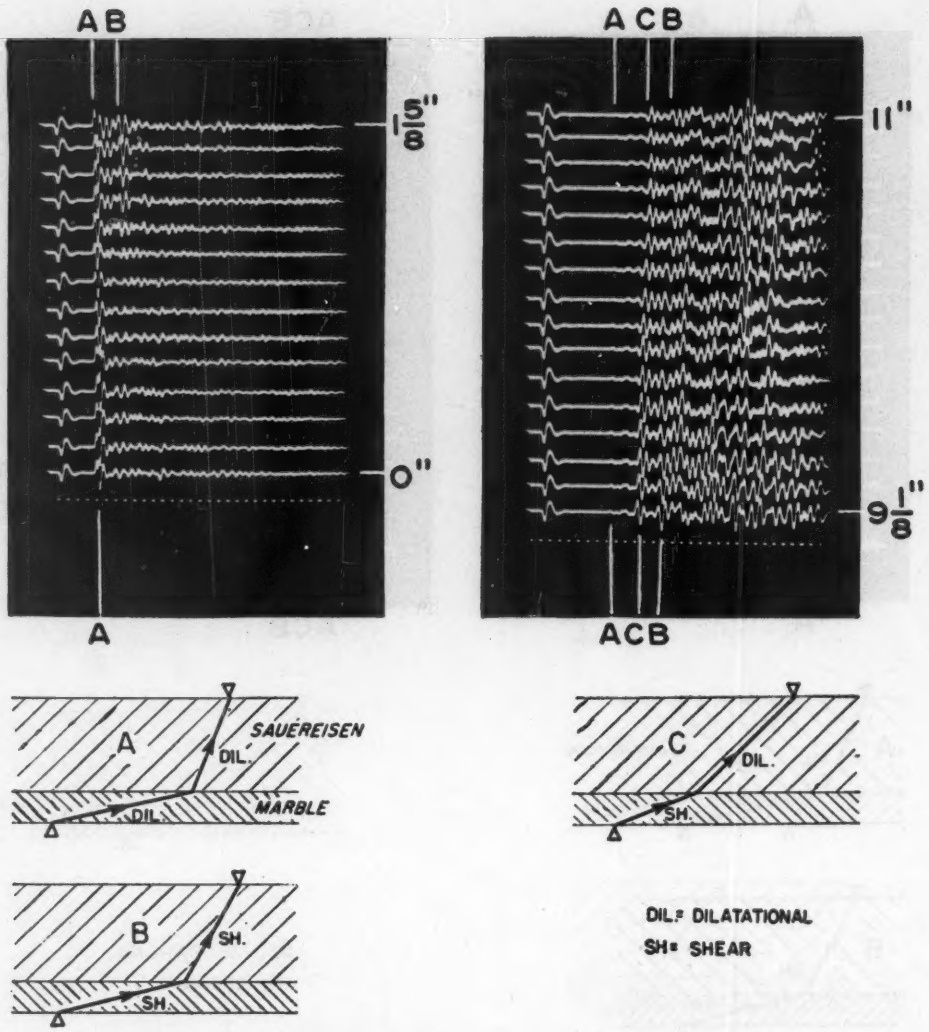

FIG. 4. Typical model records with source on marble, detector on cement.

nal from an undisturbed detector placed at one side of the profile, we have compensated for variations in input-pulse size but the mechanical coupling of the detector to the model surface remains uncertain. Four readings are taken at each position, the detector being recoupled between successive exposures, and the values of the peak-to-valley amplitudes are averaged. Figure 9 is a plot of ground roll amplitude against horizontal distance for the source and detector on the cement. The solid line is the function $A_0 e^{-0.02x}/\sqrt{x}$. The satisfactory fit and small exponent indicate that the ground roll is a surface wave (Northwood and Anderson, 1953; Lamb, 1904).

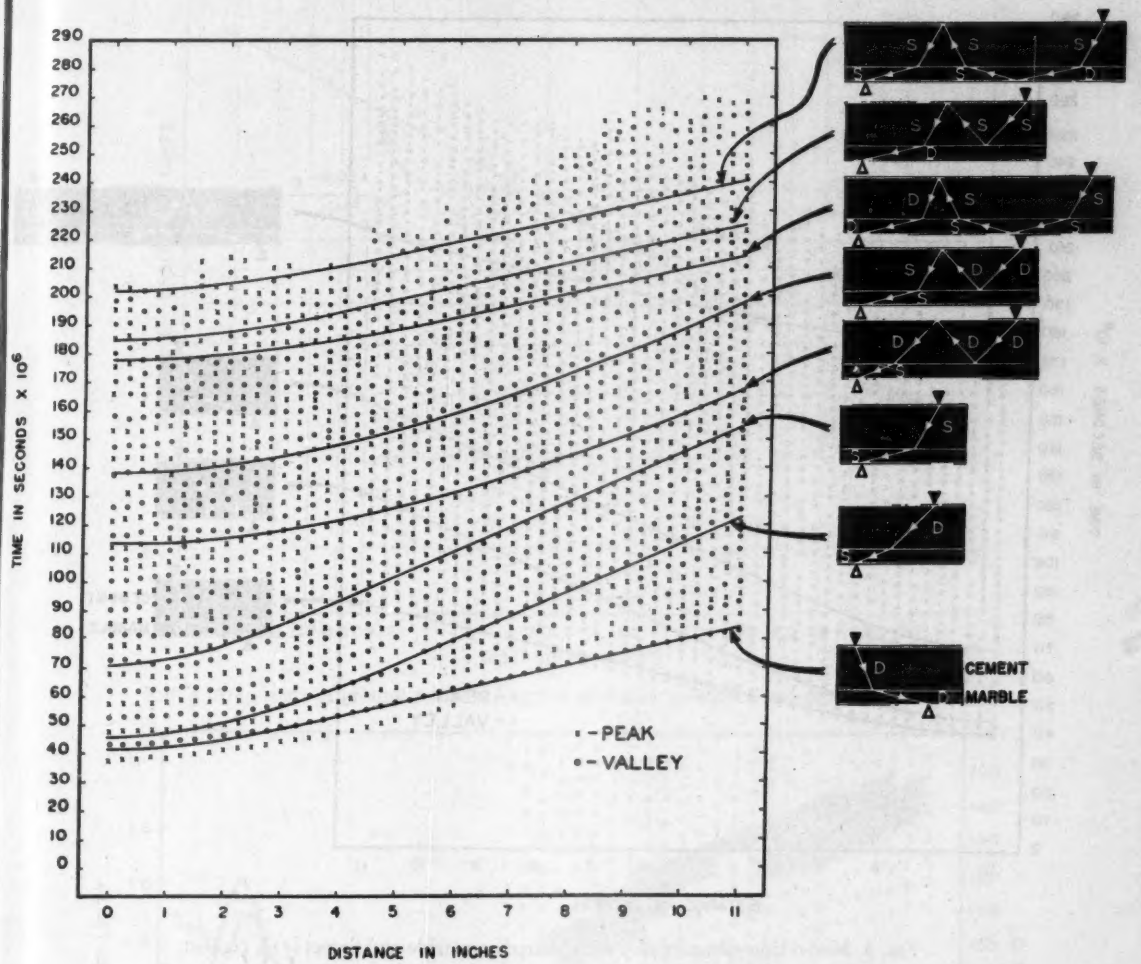

FIG. 7. Model time-distance plot with source on cement and detector on marble.

Only one dilatational event, the reflection from the cement-marble interface (event D of Figure 1), is sufficiently clear of obviously interfering events to permit amplitude measurements. The results appear in Figure 10. Theory predicts an amplitude peak at about 2.5 inches instead of at 6.5 inches as observed. The discrepancy probably means that event D is not the P_1P_1 reflection alone.

While seismic models are ideally suited for fundamental studies in elastic wave propagation, they can supply answers to problems of more immediate interest to those charged with field operation. Figure 11 represents a first attack on such a problem, that of multiple geophones. For small source-detector separations, the P_1P_1 reflection is hidden in the ground roll so that it can not be picked with certainty. Two detectors in line reduce the ground roll to where the reflec-

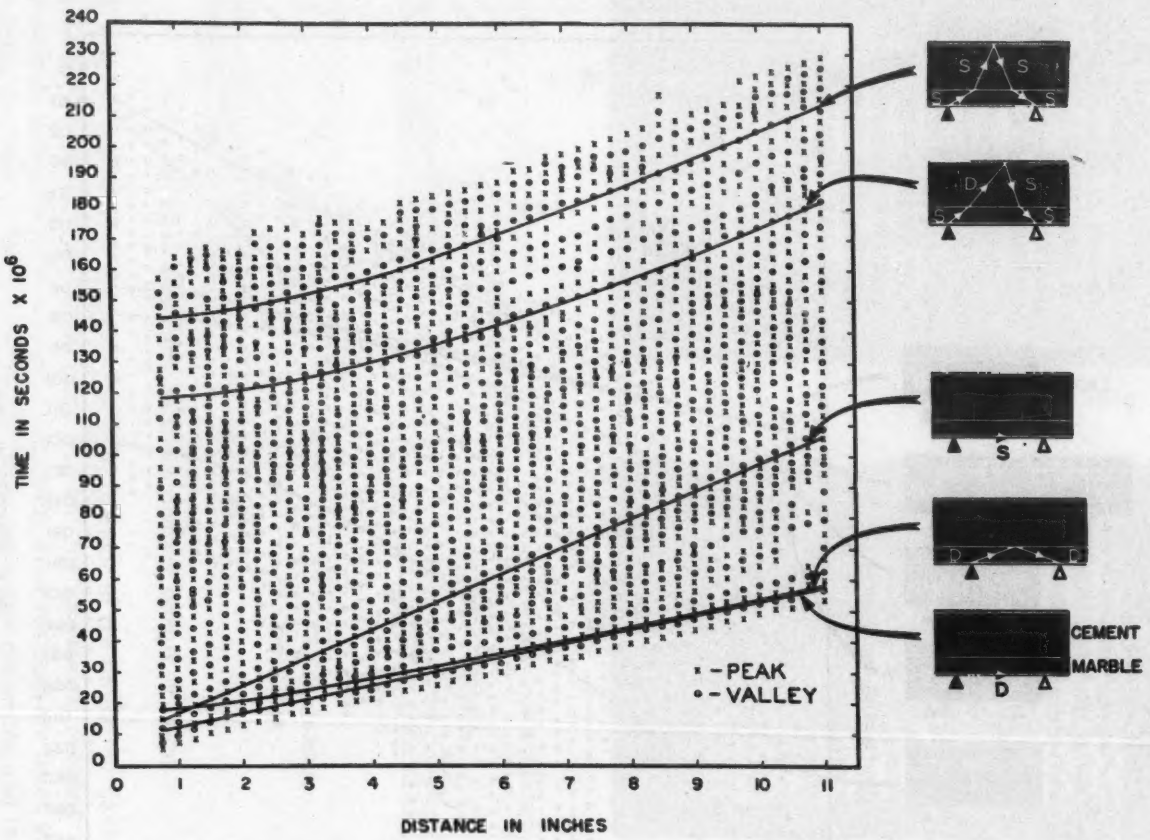

FIG. 6. Model time-distance plot with source and detector on marble.

TIME IN SECONDS X 10⁶

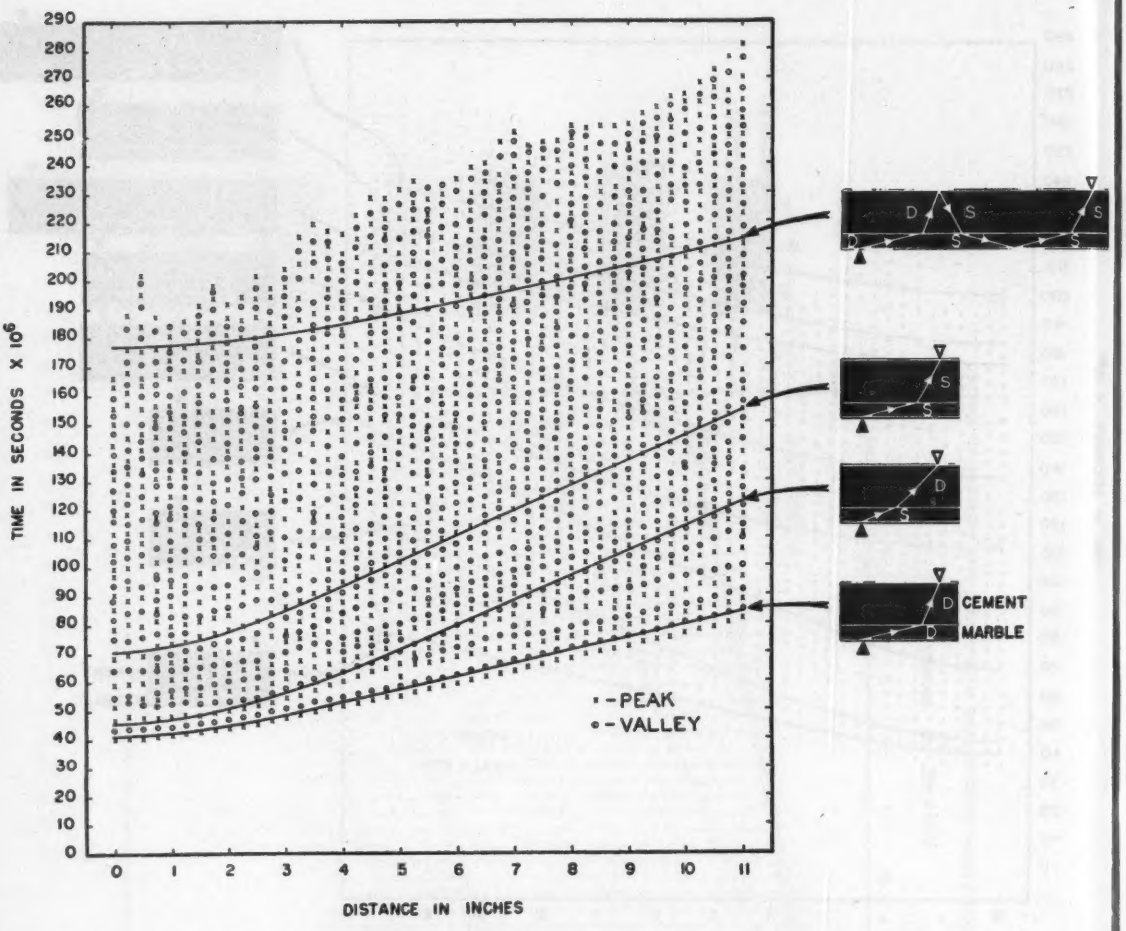

FIG. 8. Model time-distance plot with source on marble and detector on cement.

tion can be seen easily. It is anticipated that experiments of this type, properly extended, will permit a quantitative investigation of geophone patterns.

CONCLUSIONS

All four configurations possible with a two-bed seismic model have been studied qualitatively. Although some quantitative measurements have been made and explained, a general explanation of the results awaits the development of an adequate theory.

The seismograms from even such a simple section are surprisingly complex. Shear, shear-dilatational converted events, and ground roll are prominent. Neither dispersion phenomena nor pulse broadening due to attenuation have been detected for this choice of materials and bed thicknesses.

Although models appear best adapted to fundamental studies, certain field

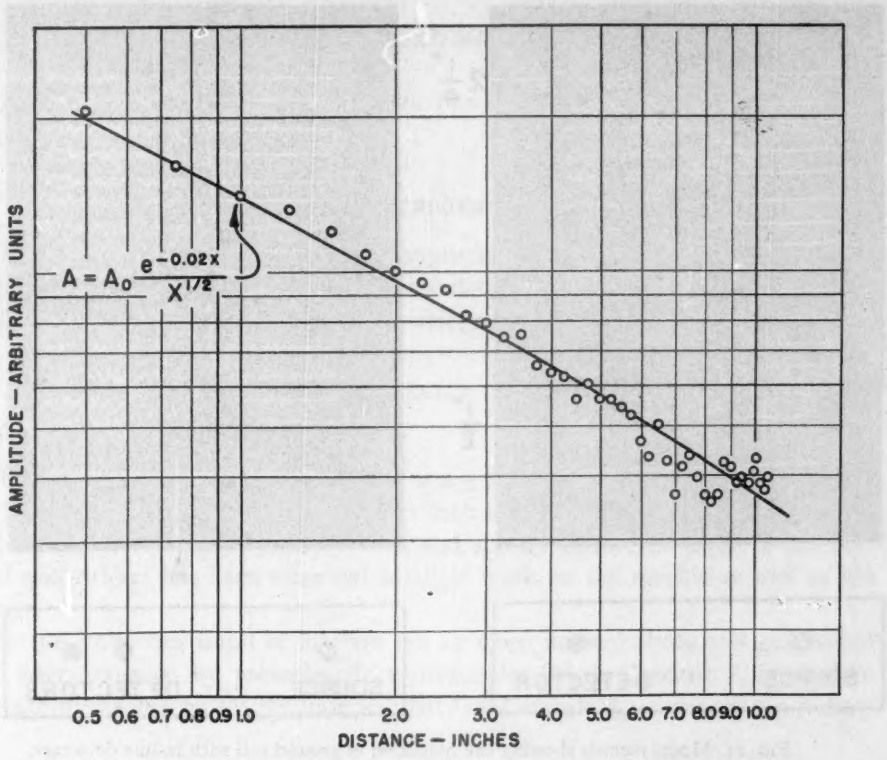

FIG. 9. Amplitude of ground roll as a function of distance—source and detector on cement.

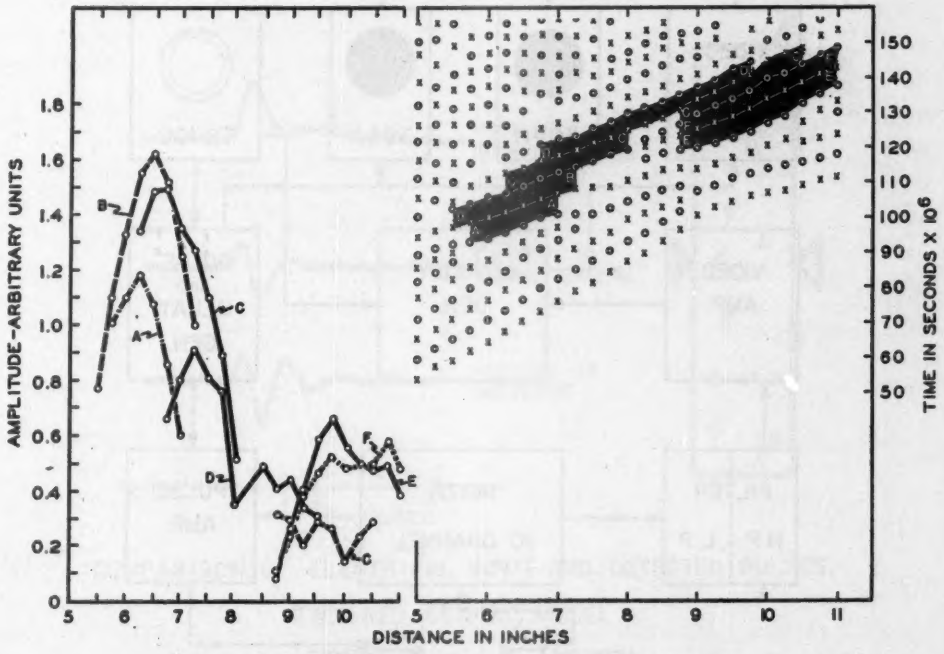

FIG. 10. Amplitude of dilatational wave reflection from cement-marble interface as a function of distance—source and detector on cement.

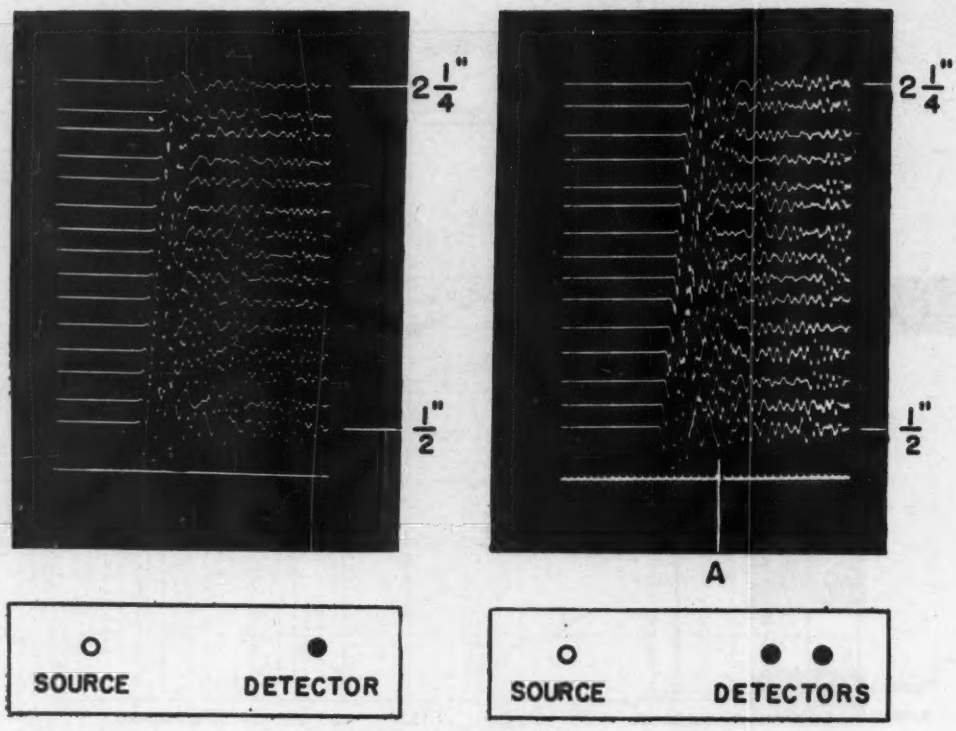

FIG. 11. Model records showing the reduction of ground roll with in-line detectors.

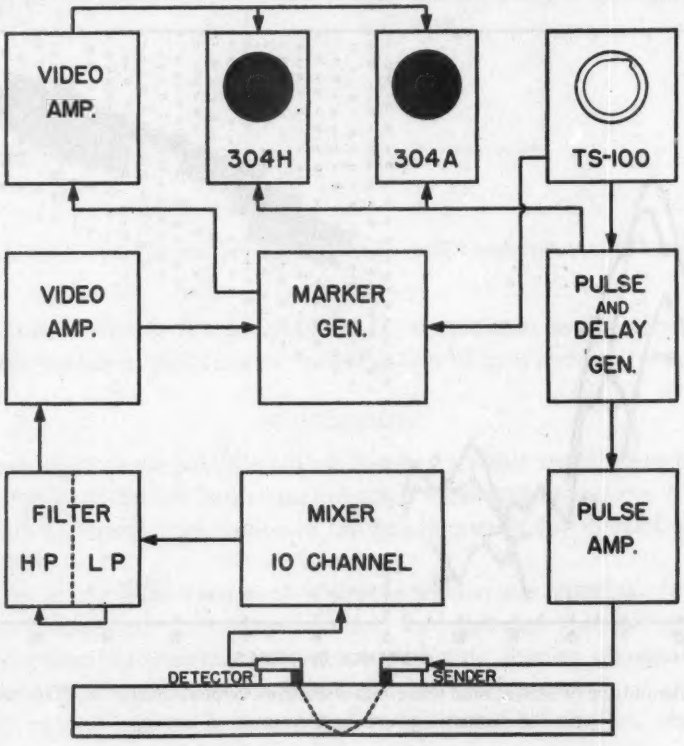

FIG. 12. Schematic of seismic model equipment.

problems can be attacked with their aid. The investigation of multiple geophone patterns is one such problem.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to The Carter Oil Company for permission to publish this paper. The assistance of Dr. C. S. Clay in preparing many of the figures is gratefully acknowledged.

APPENDIX

Model Equipment and Techniques

The two-bed seismic model consists of a 5 ft×7 ft×3 inch slab of Sauereisen No. 31 cement bonded to a 5 ft×7 ft×1 inch slab of marble. It rests on a heavy steel frame table topped with plywood and sponge rubber. A piece of the plywood and rubber has been removed to allow work on the marble as well as the cement.

In the frequency band of interest (10 to 1,000 kc/sec) shots and geophones have been replaced by piezoelectric transducers. Brush Ceramic A is used to generate ultrasonic pulses; lithium sulphate or Ceramic A, to detect the pulses.

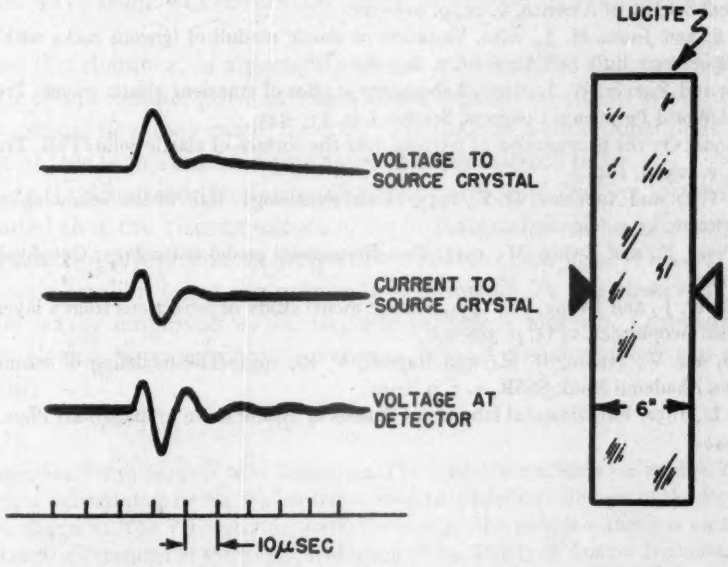

FIG. 13. Comparison of electrical input and detected pulses, two-bed seismic model.

The active transducer areas correspond to seismic shots and geophones 10.4 ft $\times$10.4 ft.

Figure 12 shows schematically the circuitry of the model. The controlling unit is a TS 100 A/P radar calibration oscilloscope modified to operate with a 100 kc/sec quartz crystal (Hughes and Jones, 1950). The source transducers are excited with 200–3,000 volt pulses at a repetition rate of 30 to 1,000 cps. Detector signals vary from a few microvolts to several millivolts and are displayed on two Dumont 304 oscilloscopes. One oscilloscope face is photographed. To obtain records similar to field seismograms, we take a series of exposures on a single film, the back of the Land Polaroid camera being moved in steps as the detector assumes successive positions. Travel times are measured to a theoretical precision of $\pm$0.1 microseconds, but, in practice, this precision is rarely realized because of the difficulty in choosing a "set" point on the broad detected events.

Typical input and detected pulses as measured through a six-inch slab of lucite are shown in Figure 13. Except for additional low-amplitude cycles, the voltage on the detector crystal has the same form as the current on the source crystal.

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GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 33–52, 12 FIGS.

ENERGY DISTRIBUTION IN EXPLOSION-GENERATED SEISMIC PULSES*

B. F. HOWELL, JR.† AND D. BUDENSTEIN‡

ABSTRACT

Three separate pulses were recognized on seismograms of ground motion resulting from explosions measured at distances ranging from 10 to 1,172 ft from the shotpoint. It is believed that the first pulse represents primarily body waves, the second pulse coupled waves, and the third pulse Rayleigh and Love waves arriving simultaneously. The ratios of the energies of the various pulses are given for several distances. The rates of attenuation of the three pulses are expressed as exponential functions and also as inverse power functions.

THEORY AND PREVIOUS WORK

In an earlier paper (Howell and Kaukonen, 1954), a theory describing the formation of seismic waves near an explosion was presented. It was postulated that in the ideal case, in a homogeneous, infinite, non-fluid medium, a spherical cavity is formed by the pressure of the expanding gases. Part of the energy of the explosion is used in heating the gases in the cavity; the rest is imparted to the rock in the form of a shock wave. Much of the energy of the shock wave will be used to fracture the rock. At some distance, this fracturing and the increasing area of the wave front will reduce the maximum stress to the breaking strength of the rock.

Beyond this distance, in a perfectly elastic medium, the energy will be transmitted as a compressional pulse in which strain is proportional to stress. In actual materials, plastic flow may cause the rock to deform in a time-dependent manner. The effect of this is to absorb energy from the transmitted pulse.

Born (1941) discussed the nature of viscous and solid friction losses in rocks. He concluded that the viscous nature of earth materials is not an important factor in attenuating vibrations at frequencies of less than 150 cycles per second, and that solid friction losses are primarily responsible for the observed attenuation of the waves employed in the seismic reflection method. Lampson (1946) derived a relation between particle velocity, v, and distance from the shot, X, of the form:

$$v = v_0 X^{-P}, \qquad (1)$$

* Contribution No. 53-19, Coll. Min. Industries, The Pennsylvania State University. This paper is a summary of a dissertation by Mr. Budenstein submitted in partial fulfillment of the requirements for the M.S. degree at The Pennsylvania State University. The complete thesis is on file in the University Library. Presented at the Regional Meeting of the Society at Boston December 27,1953. Manuscript received by the Editor April 2, 1954.

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where P would be expected to have the value 3.5. The observed decrease of amplitude ranged from an inverse cube power at short distances to an inverse first power at large distances.

Duvall (1953) studied the ground motions of solid rock at distances up to forty feet from explosions. He derived a similar formula, based on the theory of Sharpe (1942). He concluded that the exponent P should have the value of 1.5. His observed data corresponded in all cases to more rapid attenuation.

In terms of energy, neglecting variations in pulse shape, equation (1) is equivalent to:

$$E_p = E_0 X^{-B}. \tag{2}$$

L. G. Howell, Kean, and Thompson (1940) suggested that the rate of attenuation of the ground motion can be described by an exponential equation of the form:

$$v = v_0 X^{-F} e^{-\alpha X}, \tag{3}$$

where F would have the value of one for a body wave and one-half for a surface wave. In terms of energy this equation is equivalent to:

$$E_p = E_0 X^{-A} e^{-\alpha X}, \tag{4}$$

where A has the value two for a body wave and one for a surface wave. Working largely with unconsolidated materials, Howell and Kaukonen (1952) determined values of B and α.

The studies above were concerned primarily with compressional pulses. The well known seismic-wave types include, in addition, shear, Rayleigh, and Love waves. Leet (1946) and Howell (1949) have described another type of wave called a coupled wave. It is a dispersed pulse arriving after the first or principal pulse. The longitudinal component of motion is the strongest; it is recorded on more than one component; and all components are in phase with one another. In the investigation described in this paper, all these types of waves were observed. Wherever possible the rate of attenuation of each type was determined, and the amount of energy in each type of pulse was measured.

METHOD OF STUDY

The apparatus used was similar to that described by Howell (1949) and Howell and Kaukonen (1954). Seismograms were made at various distances from 10 to 1,172 feet from the shot hole. The frequency spectrum recorded covered the range from 6 to 120 cps. For each shot approximately one-half kilogram of 60% dynamite was detonated in a hole at a depth between eight and ten ft from the surface of the ground. The hole was filled with water. A new hole was used for each shot to minimize the possible change in pulse characteristics which would result from shooting more than once in the same hole. The amplitudes of the records of the individual ground motions were measured. From these, using the sine-wave

calibration curves of the recording instruments, the relative energy of each pulse was calculated.

LOCATION

The site of the field work was in an area known as The Barrens, about two miles northwest of State College, Pennsylvania. The surface rock in the region has decomposed, leaving a deep mantle of sand and pebbles. The uppermost layer is the Gatesburg formation. The site of the field work was near the crest of the Gatesburg Anticline (Butts and Moore, 1936).

The velocities of compressional waves in the first two layers were determined by a refraction survey. For the weathered layer, the value obtained was 1,830 ft/sec; for the next underlying layer, it was 4,440 ft/sec. The depth to the second layer beneath the shotpoint was estimated to be 63 ft.

RECORDED PULSES

Tracings of six of the twenty-nine seismograms used in this research are presented in Figures 2 to 7. The magnifications of the different traces are indicated at the left. The units are inches of original record amplitude per inch per second of ground velocity.

The individual pulses comprising the ground motion were recognized by their characteristic wave shapes and patterns of particle motion. They could be identified separately only where they arrived during different time intervals, or were on different components. At large distances, because of the different velocities of the various types of seismic waves, it is usually not hard to distinguish one pulse from another; but near an explosion it is difficult, and sometimes impossible, to separate them.

In order to identify the pulses, a travel-time plot (Fig. 1) and hodographs (Figs. 3 to 7) were drawn. The circles on the travel-time plot represent maximum away-from-the-shot velocities of the ground. Motion on the hodographs is given in terms of velocity, not displacement. They indicate the nature and direction of the ground motion during the passage of the pulse, but are not actual plots of particle path. The arrows correspond to time intervals of .01 second.

Three pulses could be recognized on most of the records. These pulses, labeled *A*, *B*, and *C* in Figures 3 to 7, are not clearly representative of any of the classical wave types. One unexpected characteristic was that much energy was in the transverse component. In most places, explosion-generated seismic pulses produce relatively little transverse motion.

Pulse *A*, the first pulse on the seismograms, is characterized on the hodographs by motion on all three components, but the largest motion is usually in the longitudinal component. Out to 150 feet, a distinct up-away, down-toward motion can be seen which suggests that Pulse *A* is a direct compressional pulse (Figs. 2 and 3). If *A* were a shear wave, the ground motion would be expected to be up-toward, down-away. The beginning of pulse *A* is taken as the first break on the

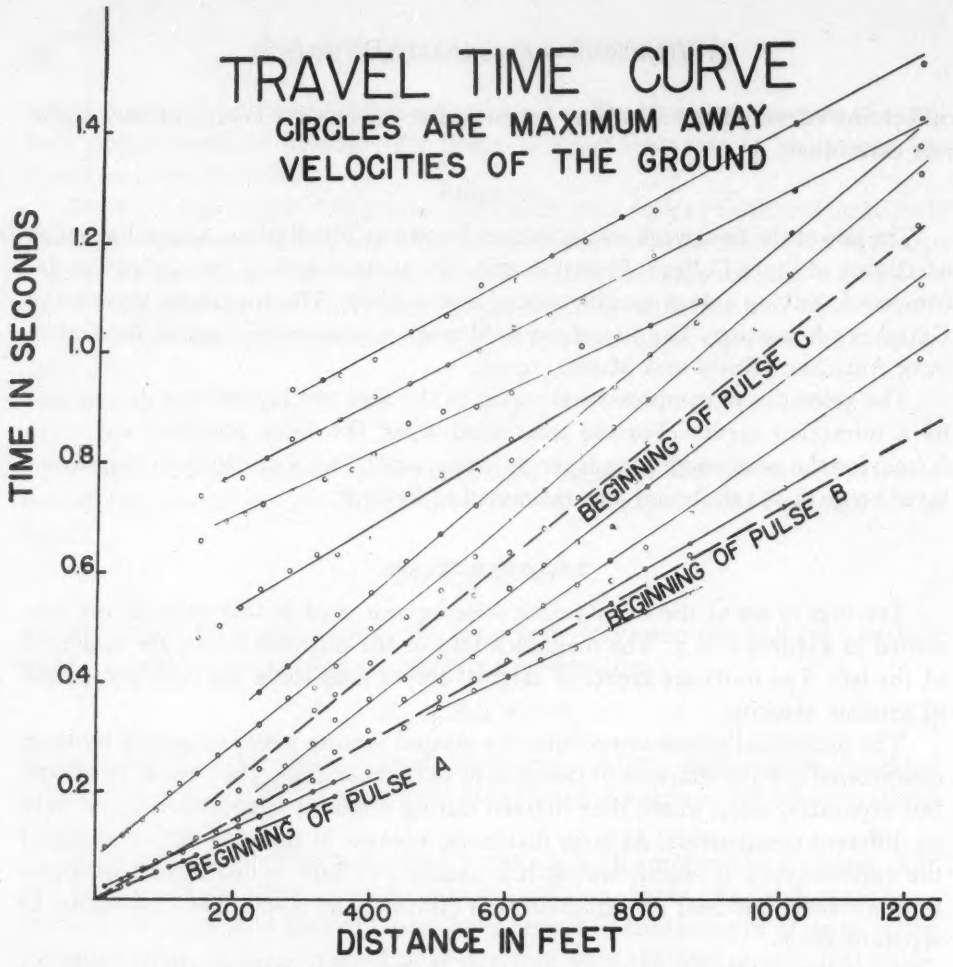

FIG. 1. Travel-time plots for all events recorded.

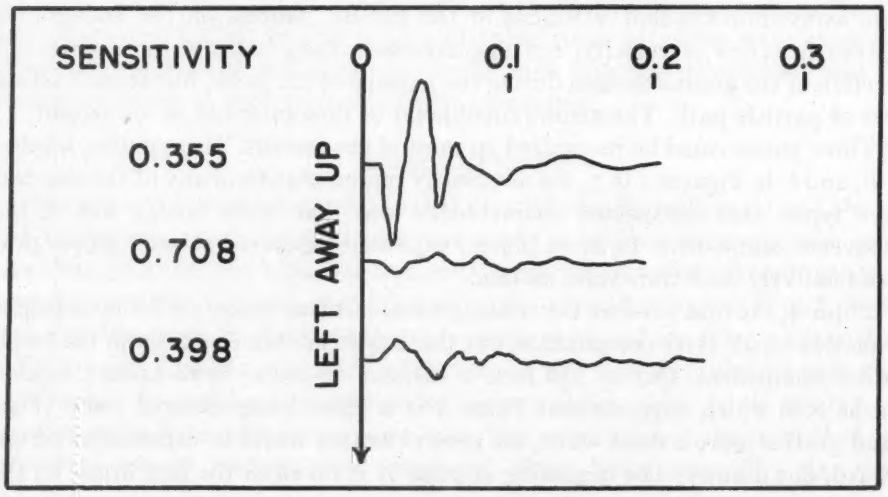

FIG. 2. Ground motion recorded ten feet from the top of the shot hole, 14 feet from the shot itself.

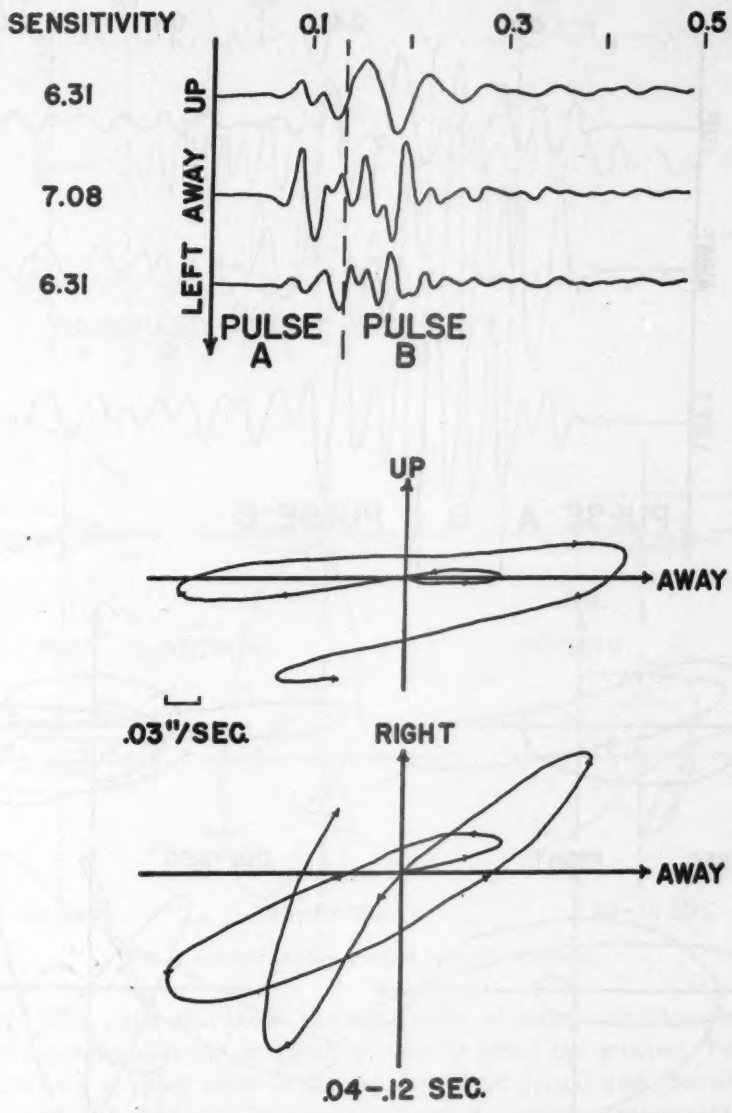

FIG. 3. Ground motion 90 feet from the shotpoint.

record near the shot and it is assumed to continue until Pulse *B* becomes the predominant pulse. Beyond 150 feet, refracted compressional waves were observed arriving before Pulse *A* in a few cases, but were everywhere so weak that their energy could not be accurately estimated. The velocity of Pulse *A* as determined by the travel time curve is approximately 1,830 feet per second. From the hodographs, it can be seen that the components of the pulse are in phase with each other. This pulse is believed to represent a compressional wave complicated

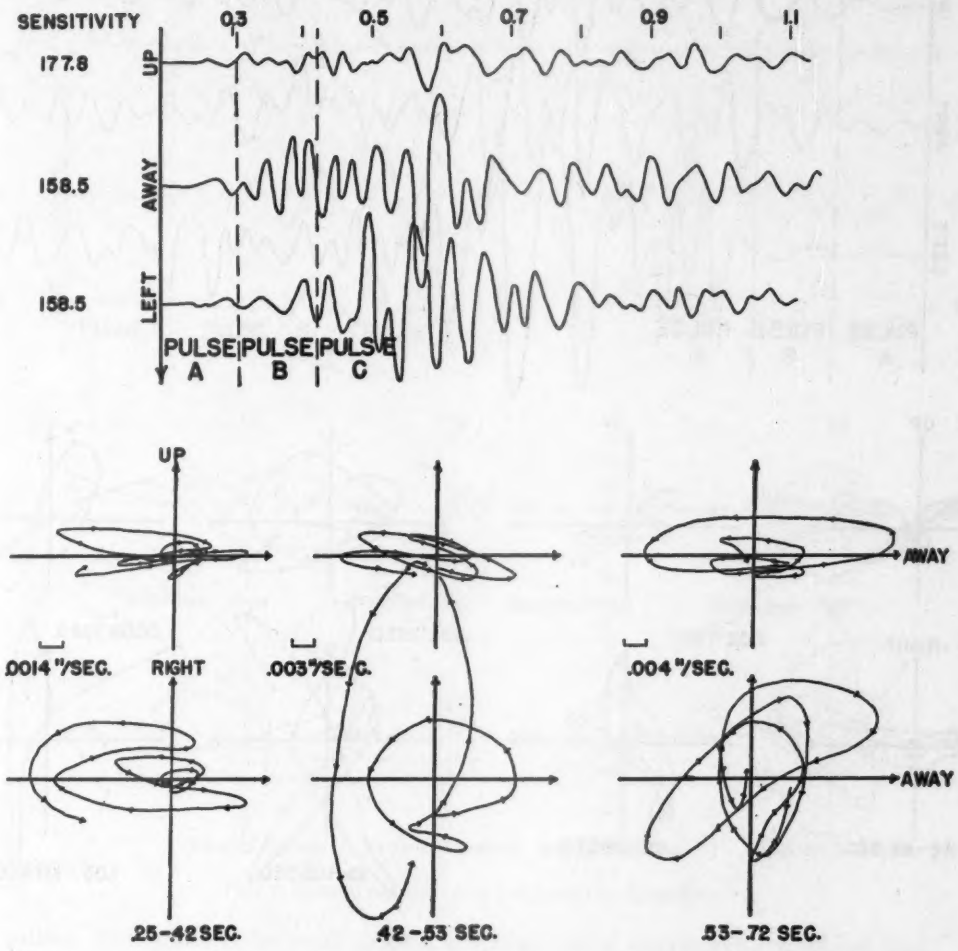

FIG. 5. Ground motion 400 feet from the shotpoint.

per second. This pulse also shows the same order of magnitude of motion on all three components, with the longitudinal usually being the greatest. Pulse *B* is believed to be a coupled wave as described by Leet (1946) and Howell (1949). It has been identified as such because in general it consists predominantly of in-phase motions on all three components; it follows the direct compressional pulses on the records, but precedes the Rayleigh waves.

The beginning of Pulse *C*, like *B*, is recognized by a change in the direction of ground motion. The ground motion tends to be most commonly elliptical, especially in the vertical plane; though often it is irregular. The transverse component is most commonly the strongest one, the vertical almost never. The amplitude of *C* often exceeds that of *B*. The beginning of Pulse *C* has a velocity of 966 feet per second. It is strongly dispersive, and lasts longer than either of the other

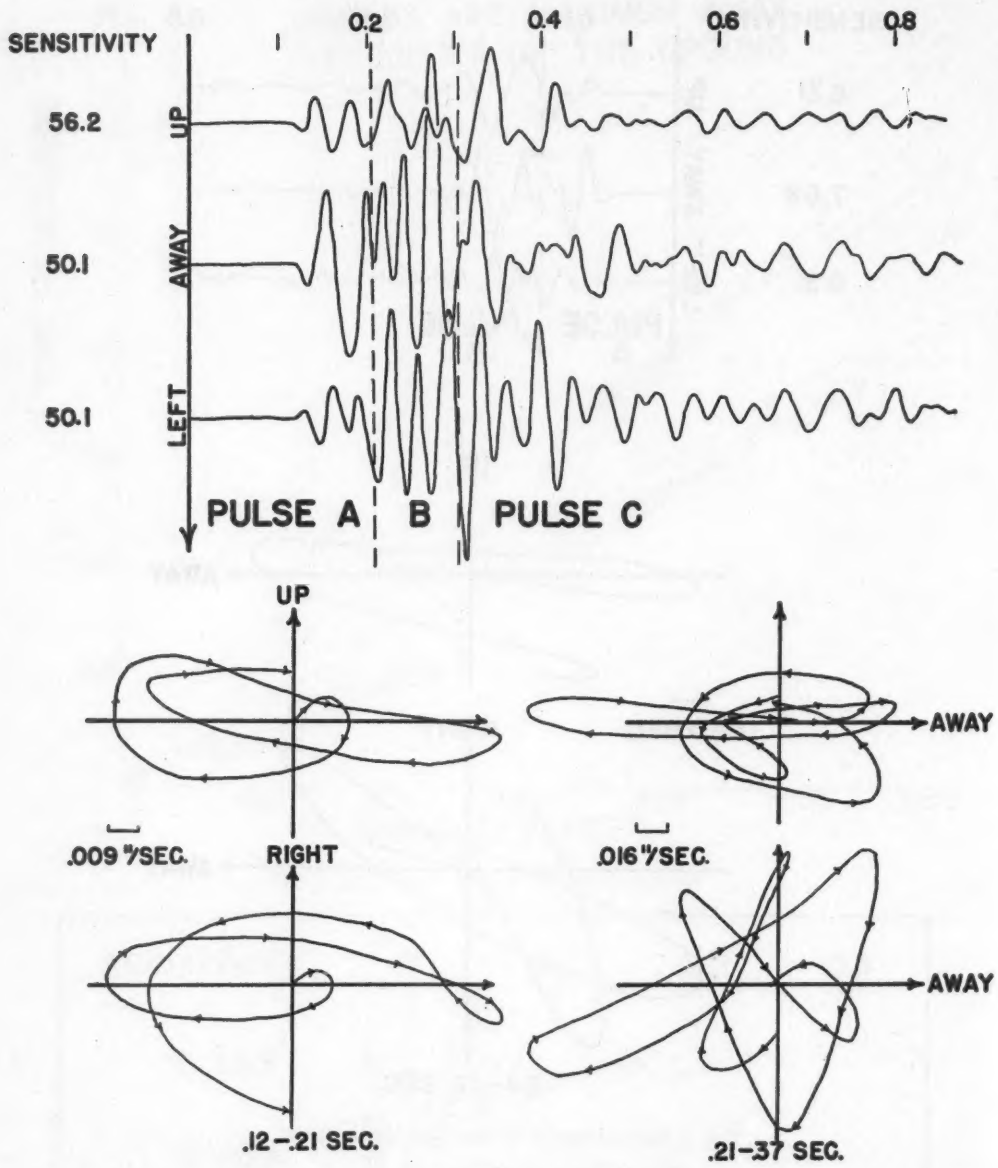

FIG. 4. Ground motion 210 feet from the shotpoint.

by inhomogeneities in the material through which it is traveling. It probably includes both reflected and refracted waves, accounting for the transverse component.

Pulse *B* is distinguishable by a change in direction of motion and often by an increase in amplitude. Its beginning has a velocity of approximately 1,380 feet

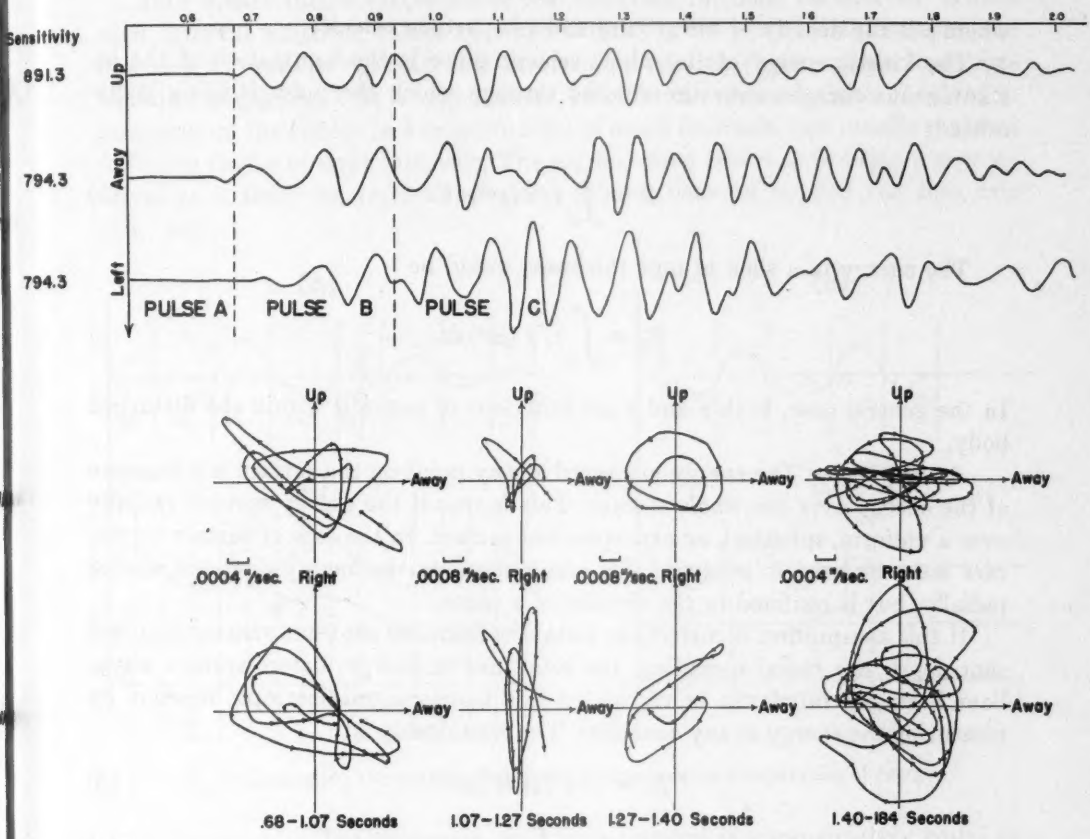

FIG. 7. Ground motion 1,000 feet from the shotpoint.

pulses. This pulse is believed to be a combination of overlapping Rayleigh and Love waves arriving simultaneously. Because of the complicated nature of the particle motion, it is impossible to subdivide Pulse *C* further and present a fair approximation of the energy content of its components.

COMPUTATION OF ENERGY

To calculate the energy represented by a complex record such as those discussed above, it is necessary to make certain assumptions. The principal ones made in this investigation are discussed below.

Assumption 1: The kinetic energy of a seismic pulse is proportional to the total energy. On the average it would be expected that one half the energy of the pulse is in the form of kinetic energy of the moving particles of the ground, and half is in the form of potential energy stored elastically in the strain of the rocks from their rest positions. The instantaneous kinetic energy per unit volume is given by:

$$E_p = 1/2\ (\rho v^2), \tag{5}$$

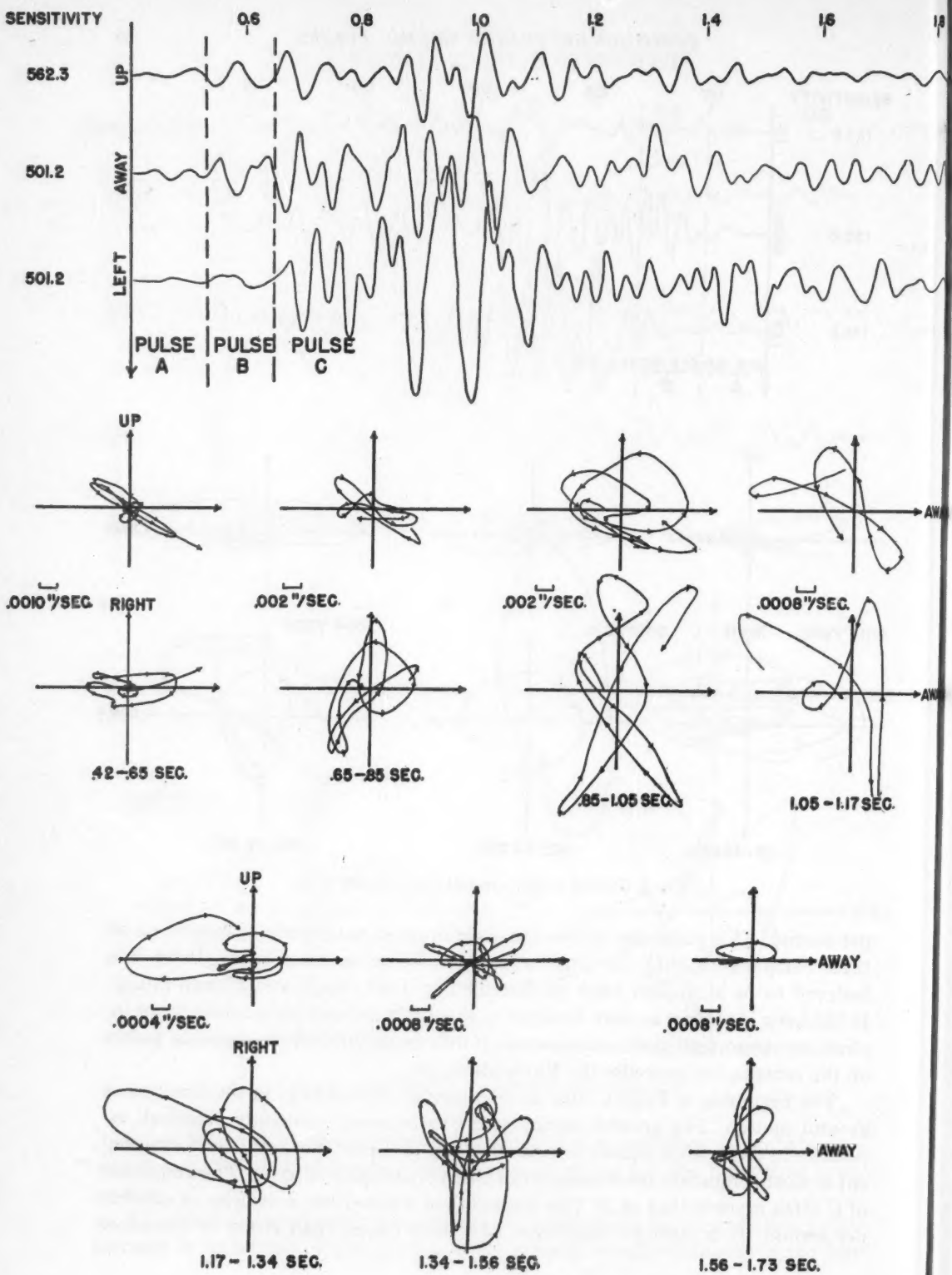

FIG. 6. Ground motion 700 feet from the shotpoint.

where ρ is the density of the ground and v is particle velocity.

The kinetic energy of the whole seismic pulse is the summation of the instantaneous energies over the volume through which the pulse is being transmitted:

$$E = \int_V 1/2\ (\rho v^2) dV. \tag{6}$$

The energy in a shell of unit thickness would be

$$E_s = \int_s 1/2\ (\rho v^2) ds. \tag{7}$$

In the general case, both ρ and v are functions of position within the disturbed body.

Assumption 2: The energy measured at any point on the surface is a measure of the energy over the whole surface. This is true if the energy spreads radially over a uniform, spherical, or hemispherical surface. In the case of surface waves, care must be used in applying this assumption, as the energy does not spread radially, but is confined to the vicinity of a plane.

If this assumption is correct, at distances from the shot not greater than the shot depth, for radial spreading, the total kinetic energy, before surface waves have been generated, can be calculated in a homogeneous, isotropic medium by measuring the energy at any one point. The relationship is:

$$E_s = 1/2\ (4\pi R^2)\rho v^2 \tag{8}$$

$$E = 2\pi\rho \int_R R^2 v^2 dR. \tag{9}$$

If c is the velocity of propagation of the energy, then

$$c = \frac{dR}{dt}. \tag{10}$$

and

$$E = 2\pi\rho \int_t R^2 v^2 c dt. \tag{11}$$

Use of this transformation makes it possible to take the integral at one distance, where R is a constant. The energy found from (11) is not the energy existing at any particular time, but is the energy flowing past a point at the distance R. Because of absorption, the amount of energy flowing through a sphere whose radius is R will decrease as R increases. Equation (11) can be rewritten:

$$E = 2\pi\rho R^2 \sum v^2 c \Delta t. \tag{12}$$

To evaluate this, a succession of real intervals, Δt, must be selected. Within each interval weighted values of v and c must be chosen. Ideally it would be desirable to make Δt so small that errors in estimating these weighted averages would be negligible. This is very tedious. In order to reduce the labor involved in summing up the energy in a large number of small intervals, one usually makes a judicious choice of large intervals. The method used here was to begin a new interval each time the trace of recorded ground velocity crossed the zero axis (Fig. 8A).

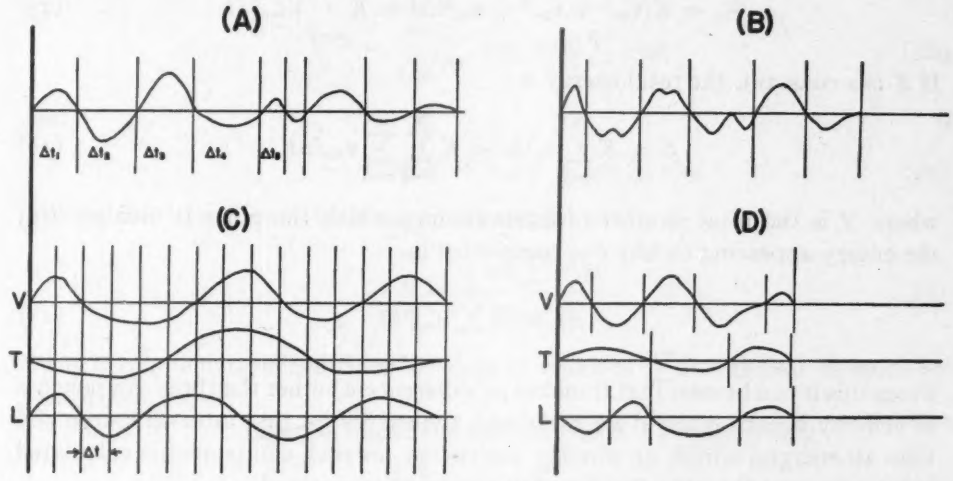

FIG. 8. Illustrating the method of choosing intervals in the computation of energy.

Assumption 3: The energy in each such interval is approximately equal to that of a half-cycle of a sine wave whose maximum amplitude and half-period are those of the recorded pulse. This assumption may introduce considerable error in some cases, such as in the second, third and fourth intervals illustrated in Figure 8B, where the trace departs greatly from sinusoidal form.

Since the pulse is recorded on several components, it is necessary to combine the energy represented by the separate traces. It can be shown in the following way that it is not necessary to divide all pulses into the same intervals. Divide all traces into short intervals of length Δt (Fig. 8C). Measure the average value of velocity in each interval on the first component getting $v_{11}, v_{12}, v_{13}, \cdots$; on the second getting $v_{21}, v_{22}, v_{23}, \cdots$; and on the third getting $v_{31}, v_{32}, v_{33}, \cdots$.

The total energy for the first time interval for a unit volume is, by equation (12),

$$E_1 = Kv_1^2\Delta t, \tag{13}$$

where

$$K = 2\pi\rho R^2 c$$

and

$$v_1 = (v_{11}^2 + v_{21}^2 + v_{31}^2)^{1/2}.$$

Therefore,

$$E_1 = K(v_{11}^2 + v_{21}^2 + v_{31}^2)\Delta t, \tag{14}$$

and for any time interval,

$$E_n = K(v_{1n}^2 + v_{2n}^2 + v_{3n}^2)\Delta t = K \sum_{m=1}^{3} V_{mn}^2 \Delta t. \tag{15}$$

If K is a constant, the total energy is

$$E = K \sum_{n=1}^{N} v_n^2 \Delta t = K \sum_{n=1}^{N} \sum_{m=1}^{3} v_{mn}^2 \Delta t, \tag{16}$$

where N is the total number of intervals into which the pulse is divided. But the energy appearing on any one component is

$$E_m = K \sum_{n=1}^{N} v_{mn}^2 \Delta t. \tag{17}$$

From this it can be seen that it makes no difference whether the three components of velocity in each interval are measured, the energy for that interval found, and then all energies added, or whether the energy for each component is calculated separately, and then the three energy components summed.

The importance of this is that it allows one to divide the different components into different time intervals (Fig. 8D). This is a great convenience and is what has been done in this research. Energy-measures, $\sum v^2 \Delta t$, were calculated using this method for the three pulses observed on each of the twenty-nine seismograms studied. For simplicity in computing pulse energies, the beginnings of pulses were always assumed to be at times when the ground velocity was zero. These times were usually not exactly the same on all three components, so this method of picking times causes a certain amount of overlap in dividing the record into separate pulses.

RATES OF ATTENUATION

If the energy spreads radially in all directions, the energy flowing through a surface element of unit cross section perpendicular to a radial line at radius, R, can be found by dividing the energy represented by equation (12) by a number numerically equal to the area through which the energy is spreading:

$$E_p = \frac{2\pi\rho R^2 \sum v^2 c \Delta t}{4\pi R^2}. \tag{18}$$

If the velocity of transmission is constant for the whole pulse, the energy flowing

past a point at distance R is:

$$E_p = \frac{\rho c}{2} \sum v^2 \Delta t. \tag{19}$$

Therefore, under these conditions, the energy-measure, $\sum v^2 \Delta t$, is proportional to the energy flowing through a unit area at a given point. This energy-measure has the units cm²/sec in the cgs system.

By comparing (19) and (2) it is apparent that

$$X^{-B} = \frac{\rho c}{2E_0} \sum v^2 \Delta t = C \sum v^2 \Delta t, \tag{20}$$

and

$$-B \log X = \log C + \log \sum v^2 \Delta t. \tag{21}$$

Taking the derivative of both sides with respect to $\log X$,

$$-B = \frac{d \log \sum v^2 \Delta t}{d \log X}. \tag{22}$$

Thus B can be determined from the slope of a plot of $\sum v^2 \Delta t$ against distance on logarithmic paper.

Similarly, by comparing equations (19) and (4) it is apparent that

$$e^{-\alpha X} = C X^A \sum v^2 \Delta t, \tag{23}$$

and

$$-\alpha X = \ln_e C + \ln_e (X^A \sum v^2 \Delta t). \tag{24}$$

Taking the derivative of both sides with respect to X,

$$-\alpha = \frac{d \ln_e (X^A \sum v^2 \Delta t)}{dX}. \tag{25}$$

Thus α can be determined from the slope of a plot of $X^A \sum v^2 \Delta t$ against distance on semi-logarithmic paper. If there is a large variation of the velocity of transmission, c, this method may yield inaccurate results. Some information could be obtained in this case by using an energy-measure of the form, $\sum v^2 c \Delta t$.

Elastic theory predicts that, due to radial spreading, energy will be proportional to X^{-2} for a body wave, and to X^{-1} for a surface wave, in addition to an absorption term. Therefore, if $\sum v^2 \Delta t$ for some pulse falls off at a rate proportional to less than X^{-2}, that pulse is not a body wave.

The computed energy-measures, $\sum v^2 \Delta t$, expressed in decibels above one inch²/sec, are plotted against distance on a logarithmic scale in Figure 9. For pulse A, the rate of attenuation found using equation (2) increased from $X^{-3.0}$

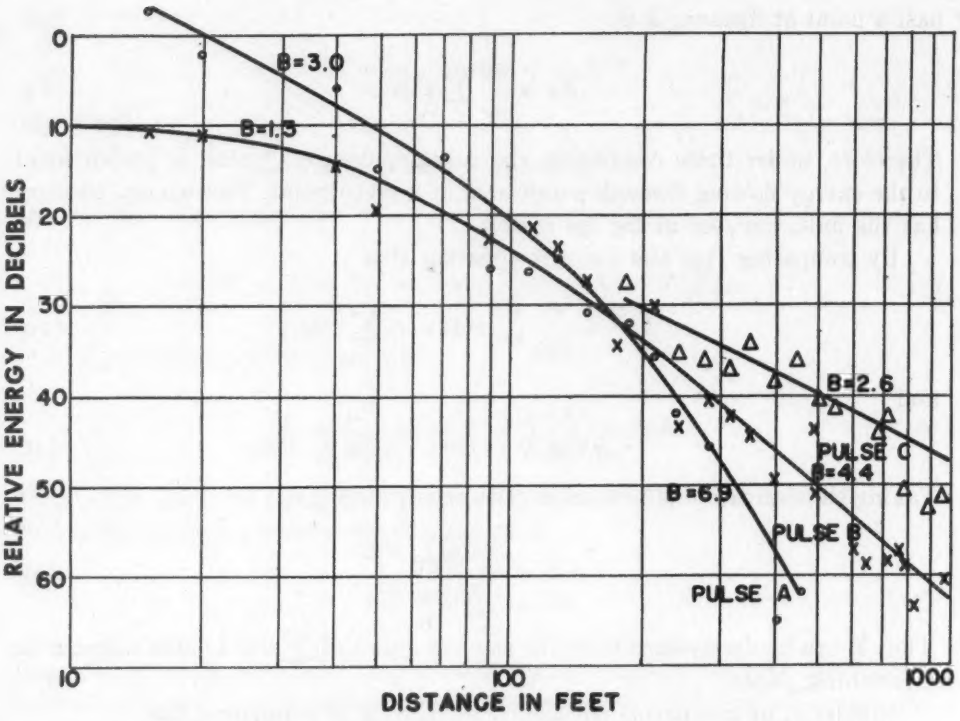

FIG. 9. Energy-measures plotted against distance for the three pulses observed.

near the shot to $X^{-6.9}$ beyond 150 feet. Therefore, this pulse could be either a body or a surface wave. Because of the direction of particle motion and because it is the first pulse on the record, it is believed to be compressional. Howell and Kaukonen (1954) found the rate of decrease to be $X^{-2.8}$ for the compressional pulse. Duvall's (1953) energy decrease varied from $X^{-3.2}$ to $X^{-5.0}$ in solid rock, since his amplitudes fell off as the -1.6 to -2.5 power. Lampson (1946) obtained figures for the exponent ranging from -2.2 to -3.8. Duvall, as well as Howell and Kaukonen, found that the exponent decreased with distance, while in the observations reported here it increased. Jolly (1953), recording in an oil well at 1,000 to 5,425 feet depth, observed a decrease in amplitude proportional to the -2.6 power of depth, which would be equivalent to the -5.2 power for energy. Because of reflection losses at formation boundaries, a larger than normal value of B would be expected in such a case. Nyborg and Rudnick (1948) report absorptions as high as 64 db per cm for high-frequency sound waves in soil.

Pulse B was treated similarly. The part from 14 to 110 feet fitted a curve whose attenuation exponent was -1.3, and from 110 to 1,172 feet the attenuation exponent was -4.4. Hence Pulse B, with an exponent of -1.3, cannot be a body pulse.

Pulse C has an attenuation exponent of -2.6. Because of its small amplitudes,

this pulse is not measureable on the records made at distances less than those for which the bends occur in the regression curves for Pulses *A* and *B*. The rate of attenuation of *C* is less than that of the body wave *A* or the surface wave *B* at the same distances. It falls off the most slowly of the three pulses. This lower rate of attenuation supports the idea that this pulse is composed of surface waves.

In Figure 10, the product of energy-measure and the square of distance has been plotted against distance for Pulse *A*. A straight line drawn through the plotted points corresponds to an exponential rate of decrease in energy of .019 per foot. Howell and Kaukonen (1954) obtained a value of .0026 in a similar in-

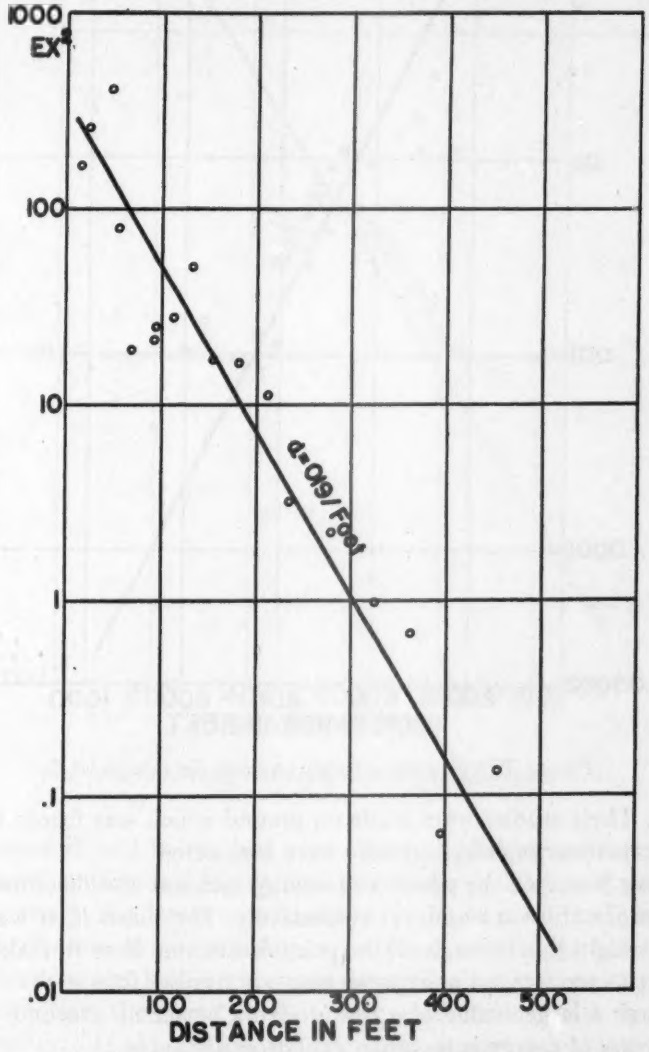

FIG. 10. Plot of energy×(distance)² against distance, pulse *A*.

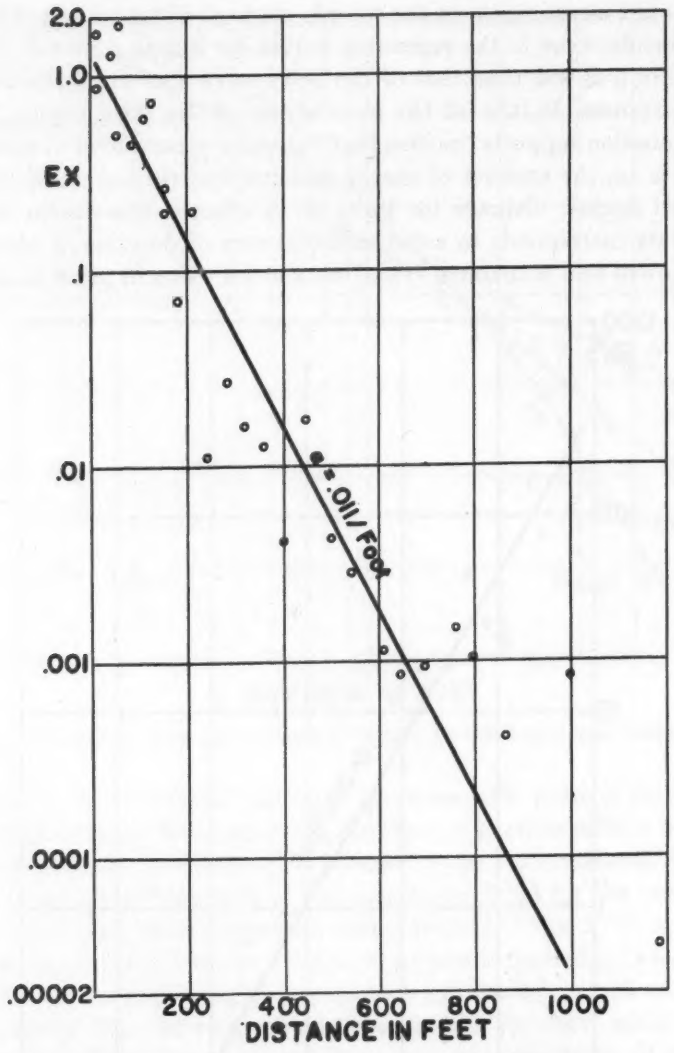

FIG. 11. Plot of energy×distance against distance, pulse *B*.

vestigation. Their studies were made on ground which was firmer than that on which the experiments described here were conducted.

For pulses *B* and *C*, the product of energy-measure and distance was plotted against distance (Figs. 11 and 12) respectively. For pulse *B*, it was impossible to draw a straight line through all the points and come close to making a reasonable fit. Out to 700 feet, a line representing $\alpha = .011$ per foot is not too unreasonable, although a larger value of α would give a better fit. Beyond 700 feet, the rate of decrease of energy is less than at shorter distances.

Howell and Kaukonen (1954) predicted that as a pulse spreads radially from

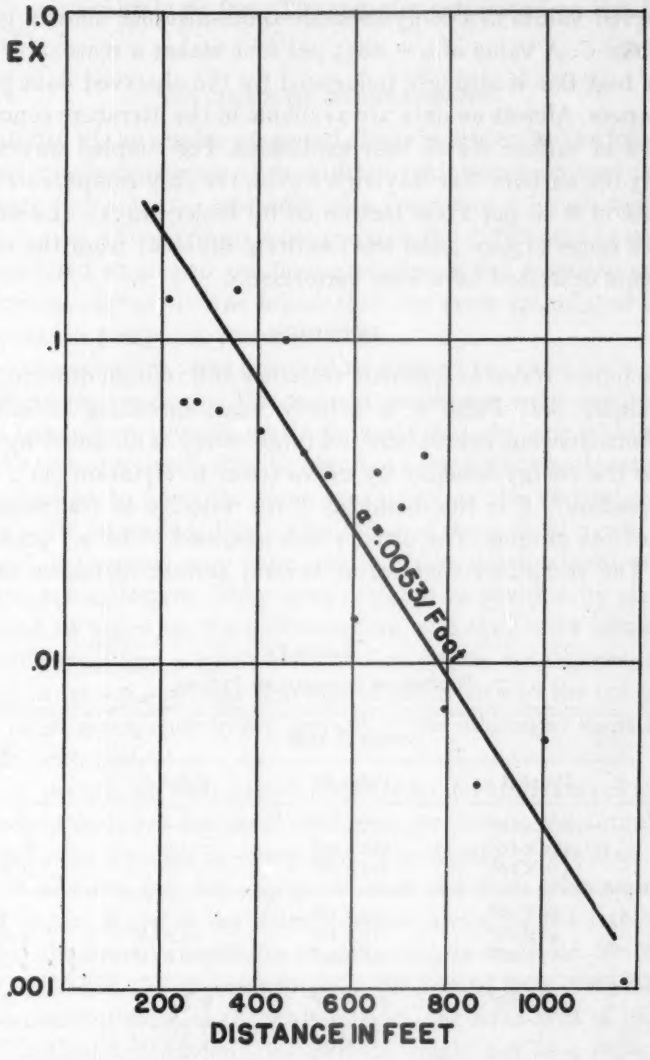

FIG. 12. Plot of energy×distance against distance, pulse C.

a shot, a distance should be reached where stress is always less than the elastic limit. For larger amplitudes, the attenuation factor is large and probably depends on amplitude. For lesser amplitudes, α would be small and possibly constant. The distribution of points in Figure 11 is such as to suggest that α may be decreasing with distance. If this represents the approach to the region of perfectly elastic behavior, then the elastic limit is very small for materials such as those underlying the test site. At 500 feet the maximum ground velocity for pulse B is only 0.008 inches per second.

The observed values of energy-measure-times-distance show a great deal of scatter for pulse *C*. A value of $\alpha = .0053$ per foot makes a reasonable fit, but the choice of the best line is strongly influenced by the observed data points at the extreme distances. Almost no data are available in the literature concerning rates of attenuation of surface waves near explosions. For coupled waves, no figures were found by the authors. For Rayleigh waves, the only comparable observation was a decrease of 8 db per 1,000 feet noted by Eisler (1952), and even this was for a distance range (1,500–4,500 feet) entirely different from the one in which the experiments described here were performed.

ENERGIES

The three pulses travel at different velocities and contain different amounts of energy. Assuming that Pulse *A* is a body wave spreading radially from the shot over a homogeneous hemisphere, its total energy is obtained by multiplying the figure for the energy-measure by $\pi R^2 c\rho$ (refer to equation (11), which is for spherical spreading). R is the distance; c, the velocity of transmission; and ρ, the density of the ground. The density was assumed to be 2.7 grams per cubic centimeter. The computed energies at several surface distances are shown in Table I.

TABLE I

ENERGY IN SEISMOGRAM PULSES

Surface distance in feet	Energy in ergs			Ratios—*A*:*B*:*C*
	Pulse *A*	Pulse *B*	Pulse *C*	
10	850×10^9	170×10^9	—	5.0 :1: —
40	$1{,}150\times10^9$	180×10^9	—	6.2 :1: —
70	530×10^9	270×10^9	—	2.0 :1: —
150	47×10^9	33×10^9	—	1.4 :1: —
180	46×10^9	10×10^9	24×10^9	4.6 :1: 2.4
400	$.17\times10^9$	$.58\times10^9$	5.0×10^9	.30:1: 8.7
450	$.38\times10^9$	2.3×10^9	9.3×10^9	.16:1: 4.0
500	—	$.56\times10^9$	4.2×10^9	— :1: 7.5
700	—	$.13\times10^9$	2.9×10^9	— :1:22
1,000	—	$.12\times10^9$	$.57\times10^9$	— :1: 4.8
1,172	—	$.0048\times10^9$	$.10\times10^9$	— :1:22

The energy of pulse *B* was computed in a similar manner, assuming it to be equal to the energy of waves of identical amplitude at the surface spreading evenly over a cylindrical surface of height 63 feet (the thickness of the first layer). For Pulse *C*, it was assumed that the energy was equal to that of a wave evenly distributed in a layer of thickness equal to a wave length, and no energy beneath that depth. The predominant frequency in this pulse was about 15 cycles per second. Using the velocity of the beginning of the pulse, the wave length was

found to be approximately 64 feet. The energies calculated on this basis are also shown in Table I.

PRECISION OF MEASUREMENTS

The reliability of the results presented above is subject to the following limitations. All the calculations were made without taking into account the variations in seismometer and amplifier response with frequency (± 3 db variation in the range 6 to 120 cps). Comparisons were made of the differences in energies which would be measured at 90 and 500 feet, assuming a flat response and using the actual calibration curves; it was found that the error introduced by assuming flat response was in every case less than 1 db.

All of the seismometers were assumed to respond the same for a given ground motion. Calibration curves for the vertical geophones were available from the Geophysical Laboratory records, which showed this to be true within one decibel. Because of the lack of a standard with which to compare the horizontal geophones, these were assumed to have the same sensitivity as the vertical seismometers. Such tests as could be made indicate a variation of ± 1.5 db at most.

In the field, inaccuracy may have resulted from misalignment and imperfect leveling of the seismometers. They were oriented in position by sighting at the shot hole along an arrow on the seismometers, and they were leveled by means of a carpenter's level and a spirit level. A five degree misalignment of the geophones would cause a 0.4 percent decrease of sensitivity to the component being sought, and cause a response to 8.7 percent of the motion at right angles in the plane of misorientation.

The size of the charge used varied from .48 to .60 kilograms of dynamite per shot. This weight included the cardboard wrapper; hence, the actual charge was less by an unknown amount in every case. The depths of the shot holes varied between eight and ten feet for any given shot and they were stemmed to the surface with water. None of the holes was shot twice for the data used in this research. This eliminated the effects of reshooting in one hole. Since a new hole was used for each shot, the inhomogeneity of the ground from one place to another might be the cause of some of the scatter. Also, the large area of ground behind the shots, disturbed by previous detonations, might act as a reflecting surface and thus be the source of a part or all of the large transverse ground motion recorded.

In calculating total relative energy, enough of each seismogram was used to represent the greater part of the total energy. Doubling the length of the interval for which the energy was calculated caused a change of 1% in a typical case tested. The ground motions at 90 and 150 feet from the shot were recorded using both resistive networks and electronic amplifiers in order to determine if the nature of the recording system influenced the results. The differences in energies computed from the records varied from 0 to 1.1 db. Some of the causes of the scattering of the plotted points are believed to be the variation in hole conditions

GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 53–67, 11 FIGS.

SEISMIC WAVE TYPES IN A BOREHOLE*

EMMET D. RIGGS†

ABSTRACT

Field measurements of near-surface velocity, using a multiple seismometer array within the borehole, indicate the presence of a well developed secondary event. This type of wave has been generated under controlled conditions and from its characteristics identified as an interface type, generally known as a tube wave. The accuracy of formation velocity data need not be influenced by this event if appropriate measurement techniques are used.

INTRODUCTION

Many of the practical problems of seismic exploration are directly associated with the near surface. The evaluation of near-surface effects is a constant problem for the geophysicist interpreting seismic records. Such effects may also cause difficulties in obtaining accurate seismic velocity data in "well-shooting" surveys.

Such surveys fall into two general classes. The first, normally used in deep wells requires the suspension of the detector within the borehole with charges shot in nearby shallow holes. The second reverses the relative position of the detector and the charge so that seismic velocity is measured between a shot in the hole and detectors on the surface.

In the studies to be discussed in this paper, some experimental modifications were made upon these two basic methods, and an increase in density of data as well as in speed of operation was obtained. However, variations were discovered in the data which raised some reasonable doubts as to their accuracy.

One of the experiments made use of multiple seismometers within the borehole. A record was obtained with this multiple array which was not completely the equivalent of one taken with the seismometer on the surface. If we assume that travel time between a point within the earth and the surface is the same, irrespective of whether the shot and the detector are interchanged, then the records obtained with the seismometer within the borehole and the charge fired near the surface should be similar to those obtained by the reverse process. However, a difference in appearance of the first arrivals or first breaks was noticeable, particularly if the array was used within a few hundred feet of the surface. An illustration of this type of record is shown in Figure 1. It was taken in an open core hole in Kaufman County, Texas, drilled to a total depth of 390 feet, with an array of five small velocity-type seismometers. Figure 2 shows a check on this record for which a similar shot was taken with an array of barium titanate pres-

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† The Atlantic Refining Co., Dallas, Texas. Based on material included in a thesis presented to the Graduate Faculty of Southern Methodist University in partial fulfillment of the requirements for an M.S. Degree in Electrical Engineering, August, 1953.

(stemming, hole depth, variation of compaction of the wall of the hole, etc.), variations in seismometer placement, variations in charge size and strength, inhomogeneity of the ground, and variations in sensitivity of recorders as the batteries aged.

The object of this research was to determine how much of the seismic energy generated by an explosion goes into each of the principal pulses observed on seismograms, how rapidly the amplitude of each falls off with distance from the source, and what is the cause of this attenuation. Numerical measures were found in answer to the first two questions. Much additional work must be done before the third question can be completely answered.

ACKNOWLEDGMENTS

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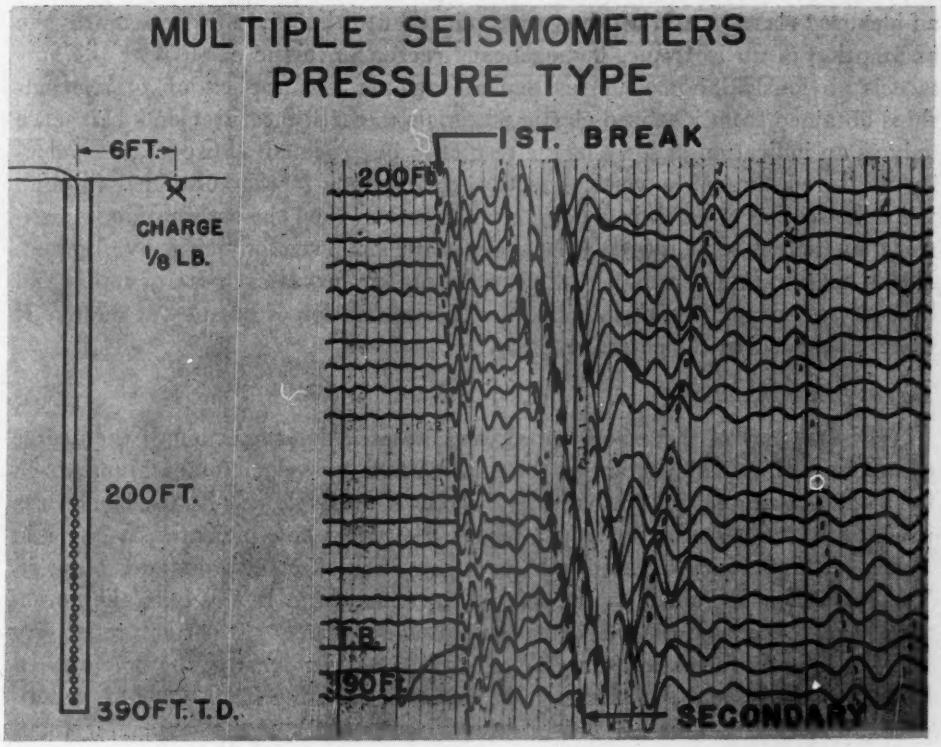

FIG. 2. Velocity survey record taken in same corehole as Figure 1. A low-amplitude first break is followed by a well developed secondary event which travels to the bottom of the hole and is then reflected toward the surface.

Sharpe (1942) has identified a secondary event as a wave associated with the fluid column. Horton (1943) assumes that a similar secondary arrival may be a shear wave generated by a reflection from the base of the surface, or weathered, layer. Wells (1949) has shown that cable-borne energy may be responsible for some of the secondary events as well as for the first breaks on velocity-survey records taken at shallow depths. Ricker and Sorge (1951) have obtained records exhibiting as many as three secondary events which they identify respectively as a shear wave, a fluid column wave, and a compressional wave which has undergone successive reflections. White and Sengbush (1953) have demonstrated the relationship between a fluid-column wave and the elastic constants of both the fluid and the solid involved.

The theoretical work of Lamb (1898) on the problem of propagation of unattenuated elastic waves through a fluid-filled hole in an elastic solid has been extended by Biot (1952) and Somers (1953) to the specific case of the fluid-filled borehole.

EXPERIMENTAL WORK

The theoretical work done on the tube wave is based on the assumption of

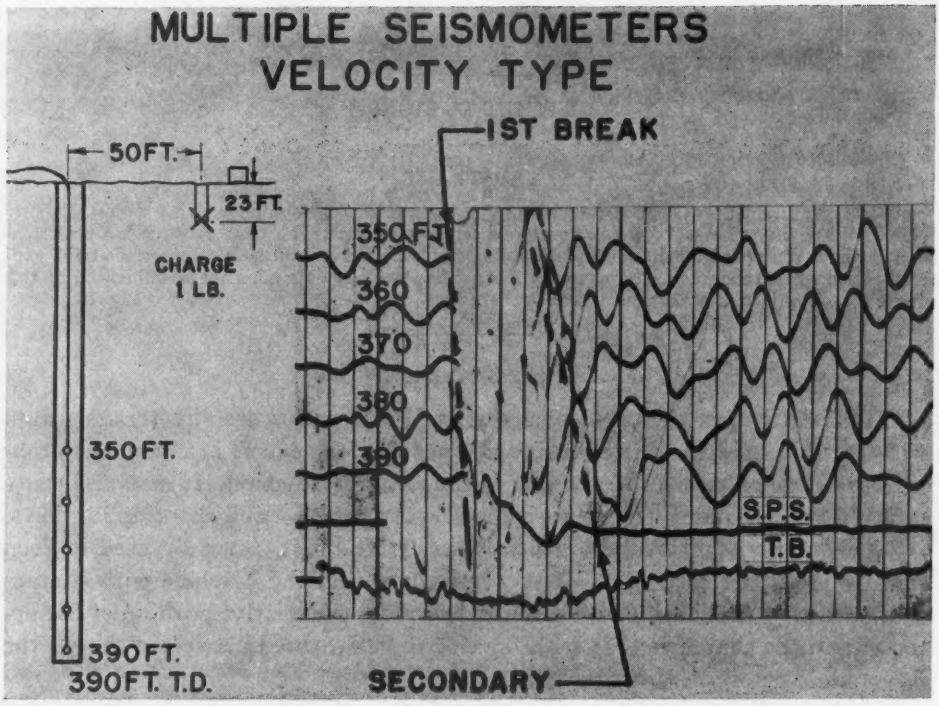

FIG. 1. Velocity survey record taken in shallow corehole in Kaufman County, Texas. Normal indications for a first break from a compressional wave through the formation are followed by an indication of a secondary event. All records taken with 17–120 cps filters unless otherwise indicated.

sure detectors in the same hole. In Figure 1, any one of the traces may be considered normal when examined alone. It is only when the five traces are examined together that a secondary event is recognized. In Figure 2, the amplitude of the first breaks is small in comparison with the secondary event; therefore, if any one of these traces should be examined separately, under proper conditions of gain and charge size, some reasonable doubt might exist as to the arrival time of the first energy from the shot.

The conclusion is soon reached that some special problems may arise in taking velocity data with a seismometer in the borehole. The primary concern is the accuracy of the interval velocity data. The presence of secondary events, so close in time to the first breaks, raised some question as to accuracy of measurement. In addition, other secondary events have been noticed with apparent velocities different from either the first arrivals or the secondary events of the type indicated. Examination of records from deep-well velocity surveys has occasionally shown evidence of some sort of secondary event which seems confined to the upper portion of the well.

PREVIOUS WORK

The presence of secondary events has been observed and reported by others.

an idealized elastic material; thus an application to the near surface requires the assumption of an isotropic, homogeneous earth. Since the earth near the surface is obviously inhomogeneous and anisotropic, the application of relationships obtained from idealized elastic materials to earth measurements can serve only as an indication of some of the results to be expected. However, if a velocity measured through a vertical section corresponds to that obtained through the same section of earth in a horizontal direction, then the assumption is justified that there is some degree of isotropy in the small section being investigated. If this qualification does not hold, then the use of theoretical work of Lamb and his successors is not permissible, because the assumption of isotropy of the elastic material is basic to the entire problem.

Isotropy Determination

The first part of the experimental work was the determination of the degree of isotropy of a small section of the near surface by velocity measurements in both the horizontal and the vertical directions. A single 500-ft cased hole was available at the start of the work. This is the center hole indicated as No. 1 in Figure 3. A nine-inch uncased hole 50 ft deep was offset at a distance of 54 ft. The No. 2 hole indicated to the left of the illustration is 675 ft to the northwest of the No. 1 hole and was drilled to a total depth of 405 ft. After a resistivity log was run and formation samples were measured for density, the hole was allowed to stand open. A resistivity log was also available from hole No. 3 indicated to the right. This hole was located 1,050 ft south of the center, or No. 1, hole. The two electric logs from the No. 2 and No. 3 holes were almost identical, so the area within the vicinity of the No. 1 and the No. 2 holes was assumed to be laterally uniform.

At the location of these boreholes the surface soil overlays a 10-ft section of Austin limestone. The next hundred feet is a uniform section of Eagle Ford shale. Velocity measurements made in the vertical direction in both the No. 1 and No. 2 holes were also identical within the accuracy of the data. Horizontal velocity in the vicinity of the No. 1 cased borehole was determined with the geophone clamped to the wall of the cased hole, the charge being lowered to the same depth in the 54 ft offset. The results are shown in the two solid curves of Figure 4, with a fair degree of homogeneity indicated for the 50-ft section around the cased borehole.

Formula for Thick-walled Tube

One form of Lamb's expression for the velocity of a wave through the fluid contained in a thick-walled tube is:

$$C = \left[\frac{\kappa_1}{\rho_1}\left(\frac{\mu_2}{\kappa_1 + \mu_2}\right)\right]^{1/2}$$

where

C = modified phase velocity of the wave through the fluid in the tube,

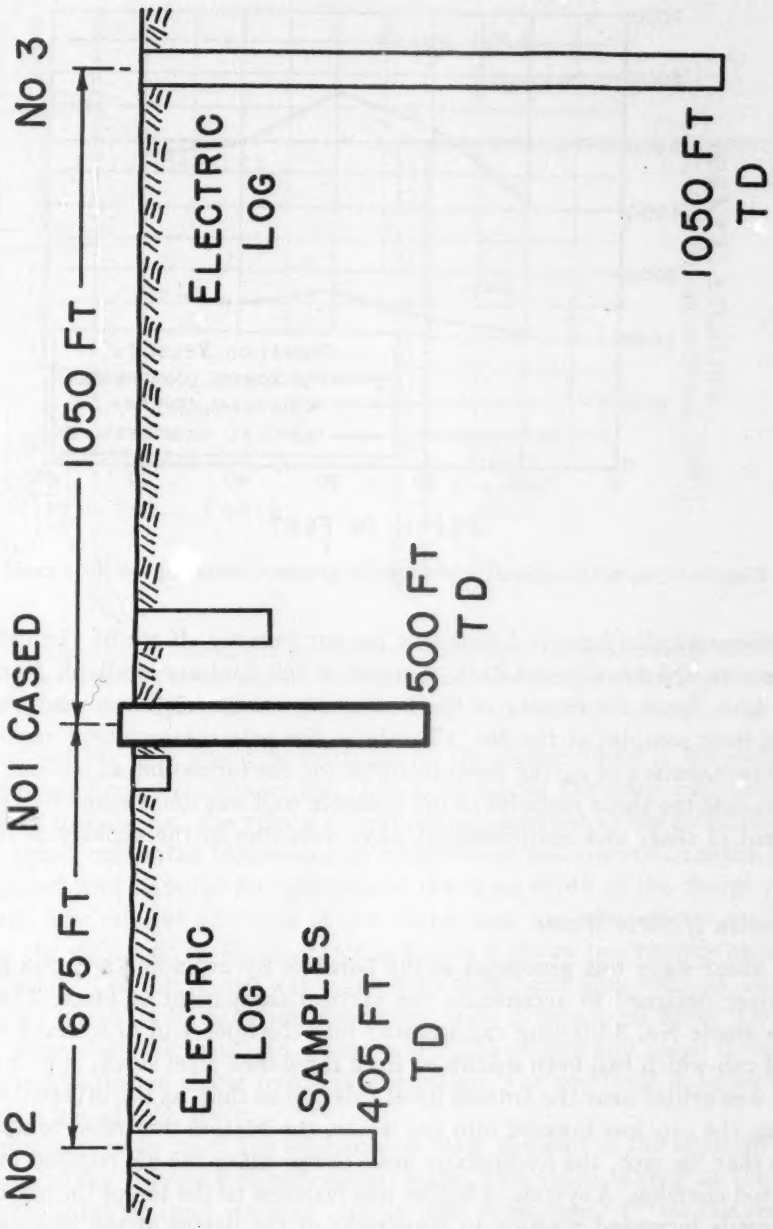

FIG. 3. Relative location of experimental boreholes in Dallas, Texas. The center cased hole is flanked on the left by a shallow cased shot hole and on the right by a 9-inch open hole.

ρ_1 = fluid density,
μ_2 = shear modulus of the solid,
κ_1 = bulk modulus of the fluid.

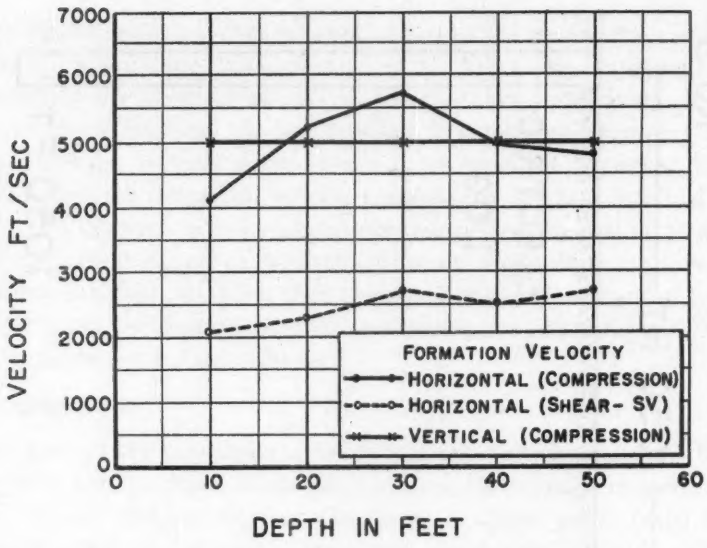

FIG. 4. Measured vertical and horizontal velocities for an area surrounding the No. 1 cased borehole.

This particular form is convenient for our purpose. If we fill the cased hole with water, the density and bulk modulus of the fluid are available from handbook data. Since the density of the formation, 2.0 gm/cc, has already been obtained from samples at the No. 2 borehole, the only measurement remaining is the determination of μ_2, the shear modulus for the formation, at various depths. In this case the shear modulus of the borehole wall was determined by the measurement of shear and compressional wave velocities in the vicinity of the borehole.

Generation of Shear Waves

A shear wave was generated in the borehole by exploding a cap in a special container designed to accentuate the vertical component of force. The charge was a single No. 8 blasting cap inserted into the open end of a heavy inverted metal cup which had been machined from three-inch steel stock. A pair of small holes was drilled near the bottom lip of this cup so that, as the inverted cup containing the cap was lowered into the water, the bottom was filled to a depth of more than an inch, the hydrostatic head compressing the air trapped inside the inverted chamber. A system of baffles was fastened to the top of the cap chamber to provide increased reaction to movement of the device at the moment of explosion. The assembly is illustrated on the left side of Figure 5. Since the specific problem at the shotpoint was the generation of shear waves from an explosion, this type of cap container was devised to distort the normal, spherical, compressional pulse in such a way that a strong vertical component was developed. The use of a cap instead of a larger charge was necessary so that the pressure

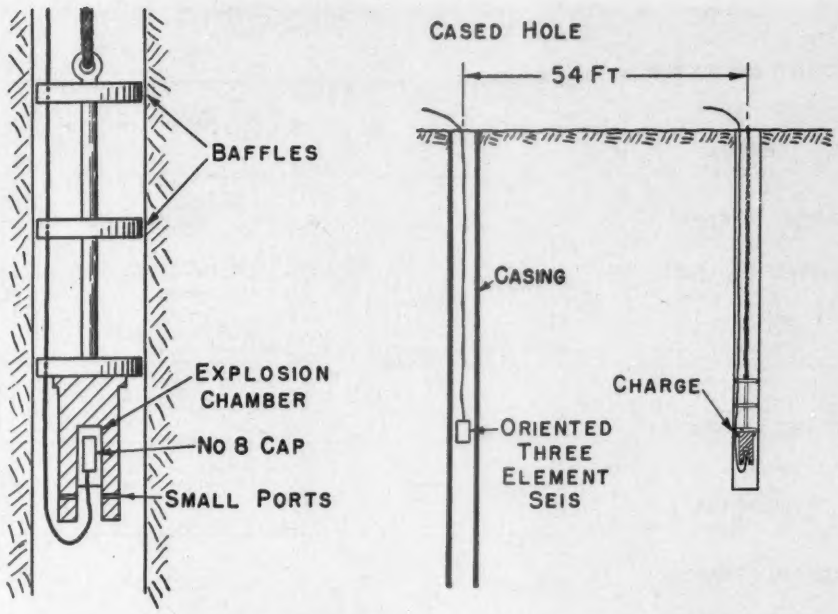

FIG. 5. Arrangement of charge and three-element seismometer in cased borehole No. 1. The seismometer was oriented and clamped into position for each measurement of horizontal shear and compressional wave velocities.

at the walls of the hole would be restricted to the elastic limits of the material. If this pressure limitation is exceeded, then a portion of the compressional wave path will be traversed at the velocity of detonation and not at the formation velocity. A small, calibrated three-element seismometer was lowered into the cased hole, oriented, and clamped into position at the same depth as the charge in the offset hole. The relative positions of the charge and the seismometer are illustrated on the right side of Figure 5, while Figure 6 shows two records obtained with the setup. The top record was taken with wide-band filter settings, and the bottom was taken under identical conditions with a 17–42 cps filter. The top record is somewhat obscured by a 60-cps power line pickup and noise; nevertheless, an examination of either record is interesting. The pertinent data are indicated to the left of each trace.

The first energy to reach the seismometer from the shot in the adjacent hole is the horizontally traveling compressional wave. This event is seen on the bottom or horizontal (in-line) trace at .010 sec and is marked "P" on the record. The second event is noticed on the two vertical traces at .021 sec and is the shear wave. The identification of these events is based on their relative times and the orientations of the seismometers on which they are detected. A series of twenty shots was taken at various depths ranging from ten to fifty feet. Some of the records show additional events which are apparently reflections from either the surface or the base of the weathered layer, but even so there is a consistent

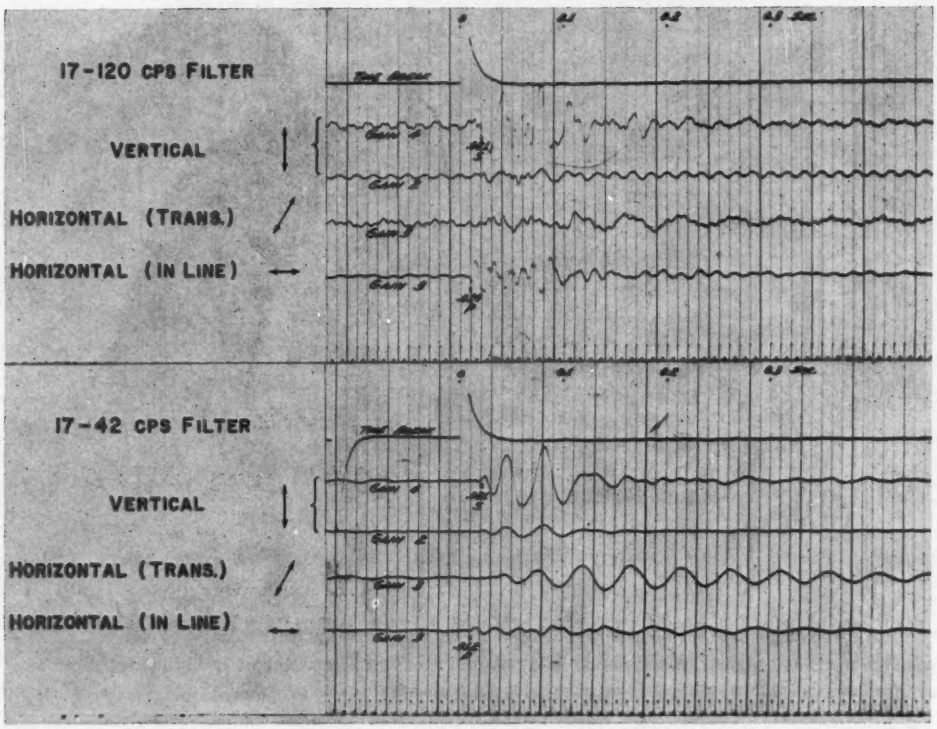

FIG. 6. Records showing shear and compressional waves transmitted through a horizontal section adjacent to the No. 1 borehole. The energy source was an electric cap shot in a manner to distort severely the normal spherical pulse and produce a shear wave.

time difference between the two events detected by the horizontal and the vertical seismometers. The times from shots within each ten-foot interval are averaged and plotted as the dotted line in Figure 4. From these two velocities and the data already available, the necessary elastic constants for the formation can be calculated.

Tube Wave in Cased Borehole

Figure 7 is a record taken in the cased hole with a No. 8 cap. The cap was fired under water tamping in a separate cased shotpoint offset 3 ft from the 500-ft hole containing the seismometer array. A monitoring system with heavily damped geophones was used to evaluate the energy released by each shot. The first energy seen on the record is from a compressional wave through the formation. At higher energy levels, or at points near the surface, a steel-casing break is evident before the formation break. The secondary event follows. The first line-up of the secondary represents a wave traveling from the shot near the surface past the array on to the bottom of the hole and then back to the surface.

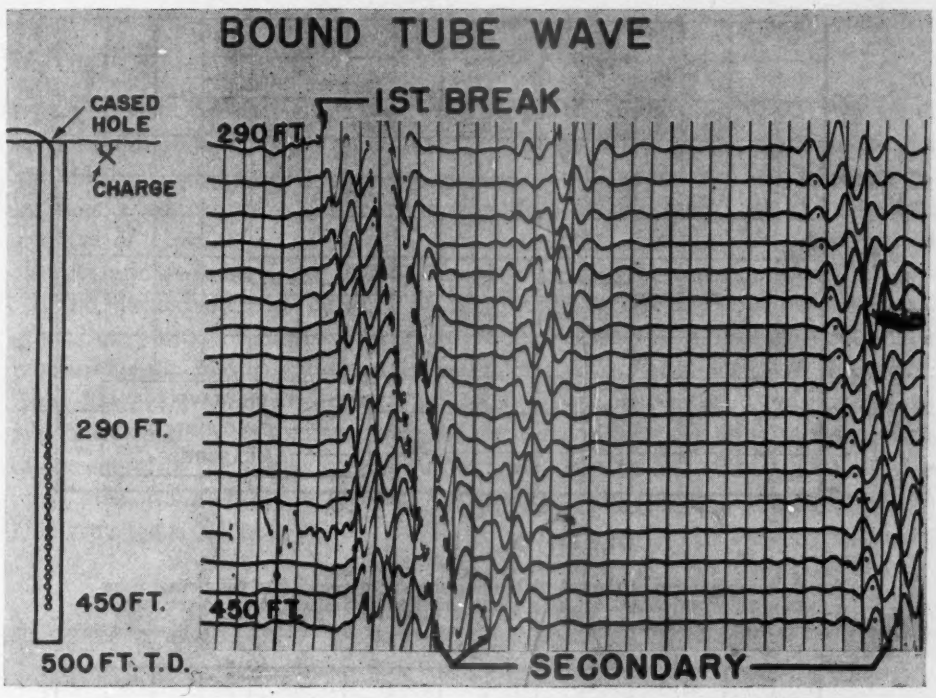

FIG. 7. Velocity survey test record, Dallas County, Texas. Made in No. 1 borehole with barium-titanate-type detectors. Energy source was a cap shot near the surface under water tamping.

The third line-up represents the same wave reflected from the water-air interface at the top. In an exceptional case, as many as ten passages of this wave along the length of the hole have been observed. Similar tube waves were observed in the uncased hole.

Considering only a 50-ft section near the top of the hole, the calculated and measured velocities of the bound tube wave are compared in Figure 8. The calculated velocities are based on elastic constants measured in the vicinity of the cased hole while the measured velocities were taken in the open hole. This No. 2 hole was originally drilled to a total depth of 405 ft and was allowed to stand open until the cuttings in the fluid column settled. At the time of these measurements, the fluid density in the upper portion of the hole was 1.01 gm/cc. Since both holes contained fluid of approximately the same density, it was possible to make this comparison.

An indication of the effect of casing on the tube-wave velocity is obtained by a similar comparison of measured velocities in both the cased and the uncased holes. This is shown in Figure 9. An increase in velocity of about 40 percent for the cased hole seems to be in order since the wave is an interface type and the $\frac{1}{8}$-inch steel wall of the casing forms the junction between the fluid column and the formation.

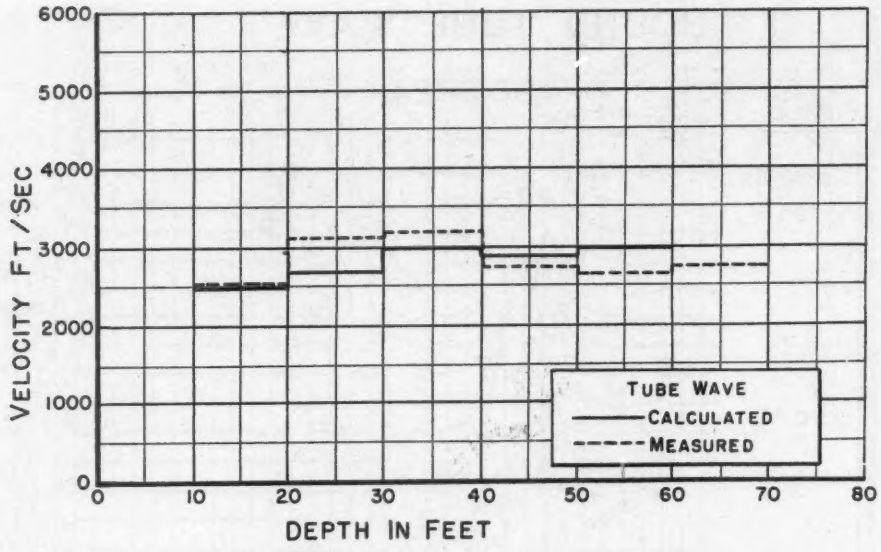

FIG. 8. A comparison of the calculated and measured velocity of the bound tube-wave in an open borehole.

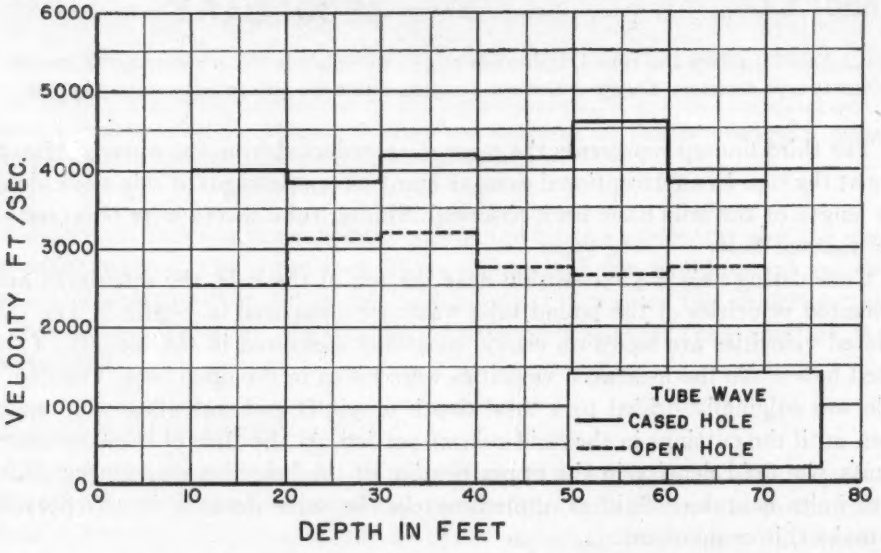

FIG. 9. A comparison of measured velocities of the bound tube-wave in a cased borehole and an open borehole under otherwise similar conditions.

For the hypothetical case in which the formation is removed from around the casing and only the fluid-filled cylinder remains, Lamb (1898) obtains the relation,

$$C = V_1\left(1 + \frac{K_1 d}{Et}\right)^{-1/2},$$

where C is the velocity of the tube waves, V_1 is the unmodified velocity of sound in the fluid, K_1 is the bulk modulus of the fluid, E is Young's modulus for the metal tube, d is the diameter and t the thickness of the tube wall. For this particular case, a velocity of 4,160 ft/sec is computed as compared with the observed average of 4,280 ft/sec. This reduction in velocity illustrates the effect of the support afforded the casing wall by the surrounding formation material.

The marked effect of the steel casing upon the bound tube-wave velocity suggests that perhaps the seismometer array, and especially the cables used in the measurements, may have an important effect upon the velocity of the wave. This, however, is not the case. The individual seismometers have dimensions which are small in comparison with the wavelength, and the cross-sectional area of the metal in the cables is small in comparison with the area of the fluid column. Measurements made with various types of seismometer arrays in the cased hole are shown in Table 1.

TABLE 1

EFFECT OF CABLE AND SEISMOMETER ARRAY ON VELOCITY OF TUBE WAVE

Type of Array	Cable Velocity	Tube-wave Velocity
1. Twenty element barium titanate—10-ft interval	6,150 ft/sec	4,310 ft/sec
2. Five geophones in core hole—10-ft interval	3,340	4,460
3. Three geophones in deep well—100-ft interval	9,000	4,340
4. Single geophone with mechanical filter		4,460
5. Miniature single geophone	1,200	4,460
6. Cased hole—Open fluid column		4,410
	Maximum variation less than four percent.	

Some of the characteristics of the tube wave were investigated with a multiple array of pressure-sensitive barium titanate elements. The five crystals used were arranged along a radius of the borehole on a light framework so that a minimum of disturbance was offered to the passage of the wave. After the system was adjusted in an open tank to give equal trace deflection with the passage of a plane wave, records were obtained at various depths within the cased hole. The advancing wave front was found to be a plane wave throughout the length of the fluid column.

Anderson and Barnes (1953) have demonstrated that dispersion is observed when a compressional wave passes along a cylindrical fluid column, but dispersive effects are not evident in this system. These measurements were taken with an optical recording system having a cut-off frequency slightly above 200 cps so that the ratio of wavelength of the highest frequency components recorded to the borehole diameter is always greater than fifty. The phase and group velocities for the tube wave under these conditions are the same, and dispersion is not a fac-

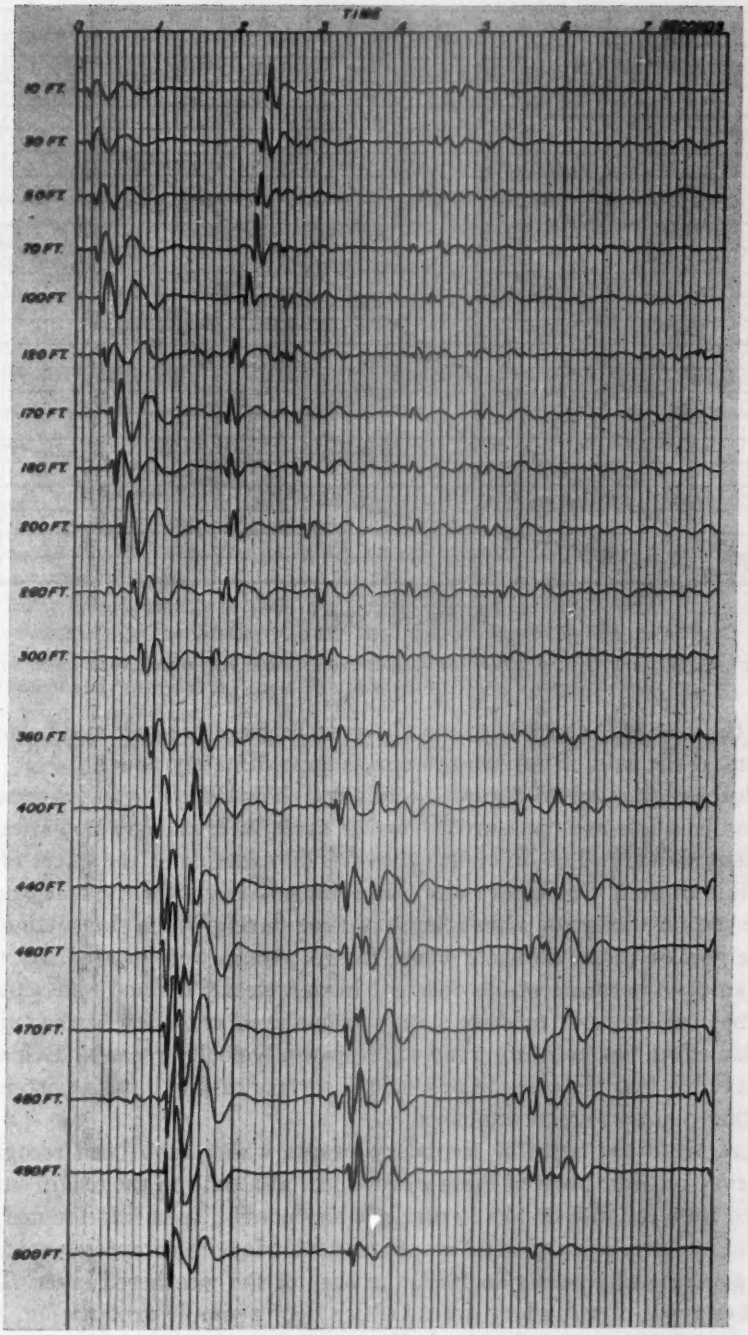

FIG. 10. A composite record illustrating the form and amplitude of the bound tube-wave at various depths. Made in the No. 1 borehole with pressure type detectors with a cap as a source of energy.

tor. The attenuation experienced by the wave is relatively small, and the geometric factor associated with a diverging wavefront is missing. The higher frequency components are attenuated more rapidly than the lower ones, so that only the low frequencies are evident after transmission of the pulse through several thousand feet of fluid column.

A composite of records taken at various depths is shown in Figure 10. A variation of trace amplitude with depth is attributed to at least two factors. The first is a slight change in sensitivity of the system with variation in hydrostatic pressure. This effect was established by retaking the data with a miniature velocity-type detector. The second factor is the phase addition experienced by the incident and reflected pulse when the detectors are located near either the top or the bottom of the fluid column.

Summary of Experimental Work

A tube wave was generated under controlled conditions and various parameters were compared with those predicted by theory. Of more direct interest are the relative velocities of three types of events observed in the cased borehole:

1. The highest velocity is that of a compressional wave, propagated down the steel casing, and commonly referred to as a casing break. This energy travels through the metal with the compressional velocity of steel and is modified only slightly by the presence of the formation or the borehole fluid. This energy is propagated through the steel at about 15,500 ft/sec and is the first indication of energy on the trace if the energy level is high enough for it to be seen at all.
2. The second event is the compressional wave through the formation. The velocity of this wave increases from 5,000 to 6,500 ft/sec with depth.
3. The third event is the tube wave, which travels with an average velocity of about 4,300 ft/sec.

A plot of these three events is shown in Figure 11. It is to be emphasized that all three events are present and will be seen on the record if the proper charge size is used. The observed amplitude of these events, in decreasing order, are the tube wave, the formation wave, and the casing break. All detectable effects of cable-borne energy were eliminated from the measurements with the aid of various types of mechanical filters.

CONCLUSIONS

Our experimental work indicates that the tube wave does not have an important effect on the accuracy of velocity determinations in boreholes. Care must be exercised, however, in choosing the relative location of the shotpoint and the size of the charge used. The ratio of tube-wave to formation-break amplitude is usually increased as the near-surface shotpoint is moved closer to the borehole containing the array of seismometers. In fact, it is possible to detonate a match-head cap at the fluid surface of the borehole and produce an excellent tube wave with no indication of energy transmitted through the formation. No detectable differ-

pendulums or to that of a series of weights suspended on springs. None of the spurious movements observed have velocities sufficiently high to interfere with the recognition of the compressional wave through the formation.

The transmission of energy through the cable is generally the most important factor that determines the accuracy of data obtained with detectors within the borehole. Either sufficient attenuation of cable-borne energy or methods of signal delay are required to insure that the first breaks are from the formation and not from the cable.

ACKNOWLEDGEMENTS

Appreciation is expressed to the management of The Atlantic Refining Company for permission to publish this material and to many of the employees of the Geophysical Laboratory for their assistance in every phase of the work.

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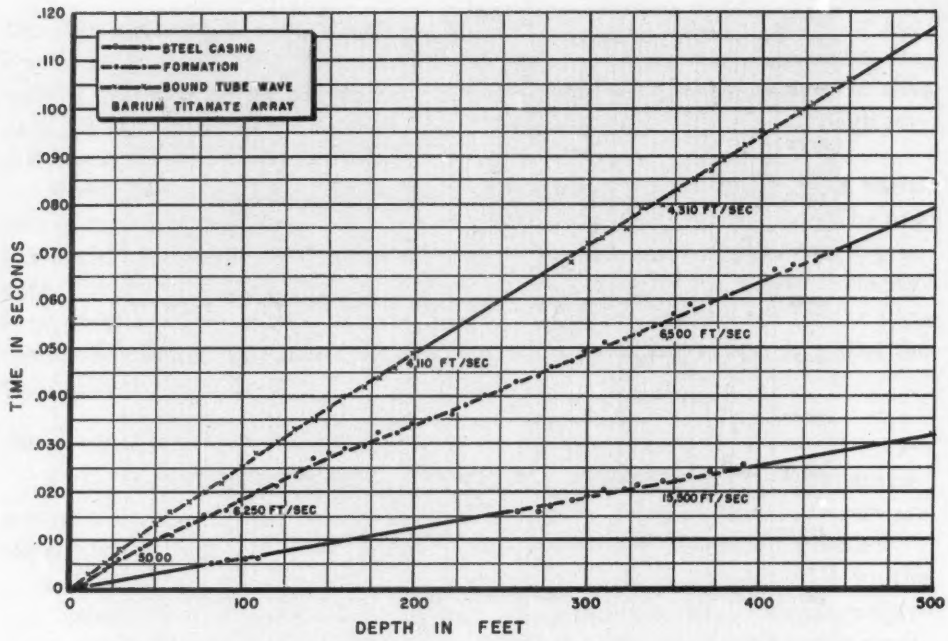

FIG. 11. Vertical travel time curves for various events measured in the No. 1 cased borehole.

ence in the time of the pick has been observed between pressure and velocity type detectors, if the gain of the two systems is approximately equal.

A close examination of Figures 1 and 2 will show that tube waves generated in the same borehole and measured over the same interval may not always show equivalent velocity. The difference provides an example of the effect of density of the fluid column. One record was taken immediately after the hole was drilled, but the second was made after a lapse of time during which the cuttings settled into the portion of the borehole where the geophones were located. By the same token, an open borehole which does not have a clearly defined reflecting surface at the bottom may not produce a very pronounced reflection of the tube wave. A similar effect has been observed on deep-well velocity records. Evidence of a tube wave has been detected in or near the surface casing, but its existence much below that point was not established.

There are other types of secondary events which have been recognized on well-survey records. Most of these waves occur at a time on the record sufficiently removed from the first breaks to preclude any possibility of interference with the events of interest. Some of these events may include both compressional and shear waves generated by reflection from the base of the weathered layer. There are still other types of secondary events which defy a simple explanation. An array of seismometers suspended within a liquid-filled borehole may undergo complicated motion in a manner somewhat analogous to the motion of a series of simple

GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 68–86, 10 FIGS.

SEISMIC VELOCITIES FROM SURFACE MEASUREMENTS*

C. HEWITT DIX†

ABSTRACT

The purpose of this paper is to discuss field and interpretive techniques which permit, in favorable cases, the quite accurate determination of seismic interval velocities prior to drilling. A simple but accurate formula is developed for the quick calculation of interval velocities from "average velocities" determined by the known x^2-T^2 technique. To secure accuracy a careful study of multiple reflections is necessary and this is discussed.

Although the principal objective in determining velocities is to allow an accurate structural interpretation to be made from seismic reflection data, an important secondary objective is to get some lithological information. This is obtained through a correlation of velocities with rock type and depth.

INTRODUCTION

Reflection measurements of seismic velocities, using only data taken near the surface of the ground, have been made for many years (Green, 1938). Continued study of this problem has led to several notable publications (Steele, 1941; Gardner, 1947; Hansen, 1947; Hansen, 1948; Savit, 1951; Widess, 1952; Brustad, 1953; Pflueger, 1954). I presented the central formula (equation (12) below) at a meeting of the *Deutsche Geophysikalische Gesellschaft* in Hannover in October, 1953, and was informed there by Dr. H. Dürbaum that this same formula was a special case of a more general one presented by him at the May, 1953 meeting of the European Association of Exploration Geophysicists in Paris. I am grateful to Dr. Dürbaum for making his manuscript available to me prior to its publication (1954). Since my treatment is very much more elementary than his and is a little closer to the practical exploration problems, I decided to proceed with its publication.

I became aware of the theoretical possibilities of determining seismic velocities from reflection records twenty years ago. But it was Curtis H. Johnson and N. R. Shade who in 1941 called my attention to the remarkable accuracy it was possible to obtain if the field work was carefully arranged. The field work was done by Western Geophysical Company, which had been doing this for some years. Early work (1938) was also done by G.S.I., under Frederick E. Romberg's initiation and direction.

A sound, but rather laborious, procedure of interpretation by successively determining interval velocities from the top layer downward was developed and used by me in 1941. From 1941 onward to 1948, I received much help from conversations with Curtis H. Johnson, N. R. Shade, Wylie R. Price, Jr., Robert Woods, John A. Legge, Jr., John J. Rupnik, Robert H. Mansfield, Maynard W. Harding, John Woolson, and Ethel W. McLemore. The idea of working in the

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neighborhood of zero horizontal distance was developed and used by John A. Legge, Jr. about ten years ago.

It would be much better if I could present an example to accompany the material that follows. This may be possible in the future. An example would have the great merit that a clear distinction could be made between simple idealized theory and the practical application of this theory. I am presuming that many of my readers will have available data that can serve for an example. The theory to follow gives most of the organizing framework which can guide practice.

FIELD TECHNIQUE

The field technique has been described by Hansen (1947). This technique has been used several years prior to 1941 by Western Geophysical Company and was used by Romberg in 1938. It is a natural extension of continuous profiling.

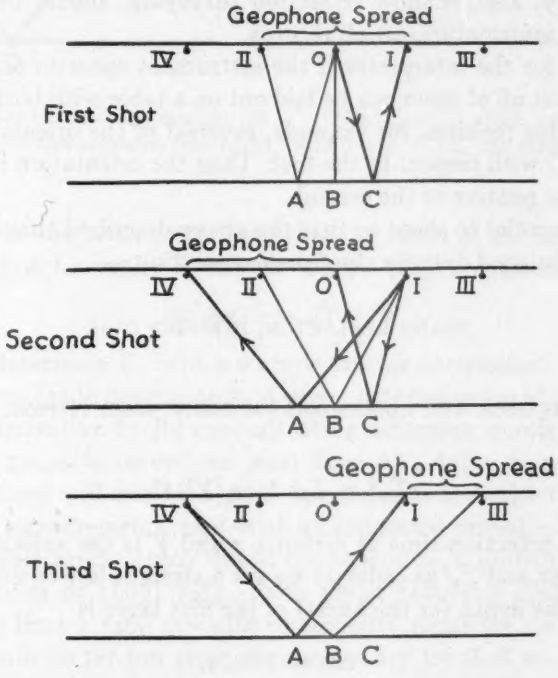

FIG. 1. Three steps in field procedure of velocity reflection profiling, showing time ties due to ray-path reversal.

The objective of the technique is to secure a large horizontal distance from source to receiver so that the slope of the x^2-T_x^2 graph may be determined with some accuracy (Dix, 1952, p. 124–126). This is done by the following combination, illustrated in Figure 1.

The first shot is a regular symmetric split. The second shot is linked to the first via the time from S.P. 0 to *C* to S.P. I and the reverse. The third shot is

linked to the second via the time from S.P. I to A to S.P. IV and the reverse. This gives a continuously-tied range of distance, x, from o to the separation between S.P. IV and S.P. III.

By exchanging positions about the central line, $0B$, we obtain another set of continuously tied records. But each new such record is also tied to one of the former set with respect to a ray reflected at the center point, B.

This procedure can clearly be generalized to 7, 9, or any odd number of shot holes.

For more complete information, especially as regards dips and curvatures of reflectors, a regular continuous profile from S.P. IV to S.P. III would be required.

Clearly every means possible should be used to make the datum correction for every trace as accurate as possible. For this, up-hole (or down-hole) shooting, and possibly, also, shallow refraction surveying, should be used, together with first break information, on all records.

It is helpful for the interpreter if the instrument operator orients his records in such a way that all of them can be laid out on a table with bottom traces tying to top traces. This requires, for example, reversal of the orientation on the second shot (Fig. 1) with respect to the first. Then the orientation is again reversed for the third shot relative to the second.

It is most essential to shoot so that the above-described time-ties can be used and also to obtain good data for the datum correction.

PLANE REFLECTOR, ZERO-DIP CASE

First Layer

This case has been well understood for many years (Green, 1938). Here we find

$$T_x^2 = T_0^2 + (1/V^2)x^2, \tag{1}$$

where T_x is the reflection time at distance x and V is the velocity, so that if we plot x^2 as abscissa and T_x^2 as ordinate we get a straight line of slope $1/V^2$ with an intercept T_0^2. The depth (or thickness) of the first layer is

$$\Delta z_1 = VT_0/2. \tag{2}$$

Second Layer

Let us look at this problem first in its simplest form. Suppose we have two layers of constant velocity V_1 and V_2. Suppose we have already determined V_1 and Δz_1 by equations (1) and (2) above. Suppose further that we have x^2, T_x^2 graphed for the second reflector. This will not plot as an exact straight line (unless $V_2 = V_1$) but will instead be a curve very slightly concave toward small values of T_x^2. Reference to Figures 2 and 3 will show the true situation very clearly. If we were always to calculate the time over straight paths, as typified

by *SABAS* and *SCDEF*, then the corresponding x^2,T_x^2 graph would be an exact straight line, say *JK* in Figure 3. But, for a geophone at *F* the least time path is say *SGDHF* and this corresponds to a shorter time than the path *SCDEF*. So the least time plots at *L* below *K*. The effect is smaller for smaller x's so that the line *JK* and the curve *JL* are tangent at *J*.

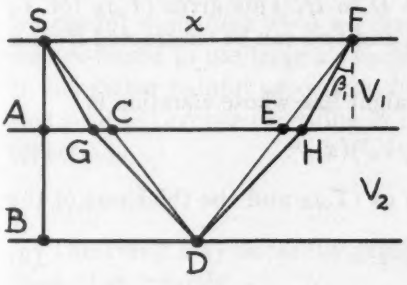

FIG. 2. Two-layer case showing straight ray paths through *C* and *E* and minimum time paths through *G* and *H*.

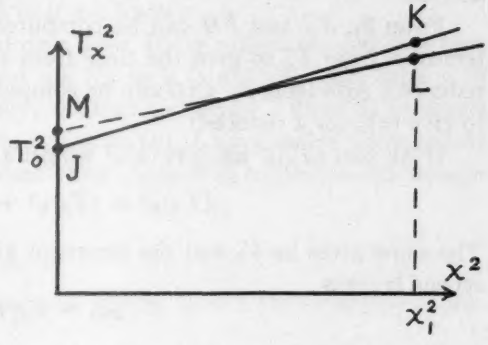

FIG. 3. x^2,T_x^2 graph curve, *JL*, with tangent line at *J*, *JK*, and tangent line at *L*, *ML*.

We shall solve the problem by removing the effect of the upper layer. First we need the angle β_1 between *FH* and the vertical (Fig. 2). We know that

$$\sin \beta_1/V_1 = dT_x/dx. \tag{3}$$

If we could determine V_1 (which we now assume determined) and dT_x/dx, we could use equation (3) to determine β_1. A direct determination of dT_x/dx would be to replace the derivative by its approximating difference quotient $\Delta T_x/\Delta x$. But as the T_x vs. x graph is curved we must keep ΔT_x down to, say, about 0.010 second or the chord will not be a good approximation to the tangent. ΔT_x requires two time measurements, each with an estimated probable error of $\pm$0.001 second in favorable cases, which would correspond to a probable error for ΔT_x of $\pm$0.0014 seconds or about 14%. Even under favorable circumstances, this would lead to at least a 14% probable uncertainty range for sin β_1 if (3) is used directly. This leads to far too great an uncertainty for β_1 if we are to use it to calculate V_2 with good accuracy.

To avoid this difficulty we draw the tangent to the x^2,T_x^2 curve at x_1 (which is easy to do because this curve is so nearly straight). We get the dashed straight line *LM*, which has the equation

$$T_x^2 = M + (1/V_{A_2}^2(x_1))x^2. \tag{4}$$

Differentiation of equation (4) with respect to x gives, at $x=x_1$,

$$T_x dT_x/dx = x_1/V_{A_2}^2(x_1). \tag{5}$$

Using equations (3) and (5) we get

$$\sin \beta_1 = x_1 V_1/(T_x V_{A_2}^2(x_1)). \tag{6}$$

Equation (6) gives β_1 in terms of quantities all of which can be measured with very high precision compared with that obtained by calculating dT_x/dx from $\Delta T_x/\Delta x$.

From β_1, SG and FH can be computed. So we can compute the time to be removed from T_x to give the time from G to D to H. This gives $(T_x)_R$ (or T_x reduced). Also from β_1, $2AG$ can be computed, and this can be subtracted from x to give $(x)_R$ (or x reduced).

If we plot $(T_x)_R^2$ against $(x)_R^2$ we get a straight line whose equation is

$$(T_x)_R^2 = (T_0)_R^2 + (1/V_2^2)(x)_R^2. \tag{7}$$

The slope gives us V_2 and the intercept gives us $(T_0)_R$ and the thickness of the second layer is

$$\Delta z_2 = V_2(T_0)_R/2. \tag{8}$$

The above calculation can be replaced by one which is somewhat simpler and much easier to apply. The above calculation does however show the principles involved in a very clear way; a generalization of this is readily extendable to more complicated cases. We now consider the simpler calculation.

Note that the x^2, T_x^2 graph (Fig. 3) may be carried right down to the immediate neighborhood of J. Indeed the tangent at J is easier to find than the tangent at L because the curve is straighter at J than at L.

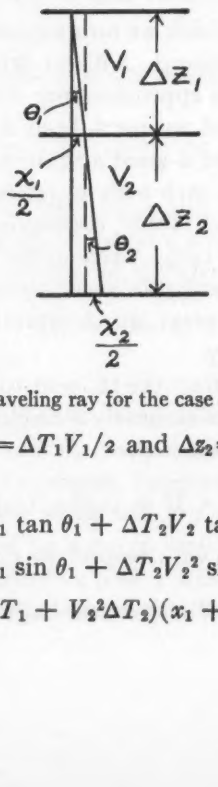

FIG. 4. Geometry of the down-traveling ray for the case of arbitrarily small x and no dip.

Refer to Figure 4. Let $\Delta z_1 = \Delta T_1 V_1/2$ and $\Delta z_2 = \Delta T_2 V_2/2$ define ΔT_1 and ΔT_2 respectively. Then

$$\begin{aligned} x_1 + x_2 &= \Delta T_1 V_1 \tan \theta_1 + \Delta T_2 V_2 \tan \theta_2 \\ &\approx \Delta T_1 V_1 \sin \theta_1 + \Delta T_2 V_2^2 \sin \theta_1/V_1 \\ &\approx (V_1^2 \Delta T_1 + V_2^2 \Delta T_2)(x_1 + x_2)/(V_{A_2}^2(0) T_x). \end{aligned}$$

Divide through by x_1+x_2. Then take the limit as $x_1+x_2 \to 0$ and the above becomes exactly (after multiplication by $V_{A_2}^2(0)(\Delta T_1+\Delta T_2)$)

$$V_{A_2}^2(\Delta T_1 + \Delta T_2) = V_1^2\Delta T_1 + V_2^2\Delta T_2. \tag{9}$$

This shows precisely what kind of average $V_{A_2}(0)$ represents. Also (9) can be solved for V_2, since all other quantities in it are known.

Note that equation (9) is only valid near $x=0$. If the reflections are such that we cannot work near $x=0$ we must not use (9) as it is not valid for large x. If we are forced to use large x's exclusively, the best procedure I know is to revert to the rather painful process leading to equation (7). I have never encountered this need in practise excepting in the case of an occasional transverse-wave-type reflection.

n Layers

This result may be readily generalized to n layers. In fact the same procedures show that, exactly,

$$V_{A_n}^2 \sum_1^n \Delta T_i = \sum_1^n V_i^2 \Delta T_i, \tag{10}$$

and

$$V_{A_{n-1}}^2 \sum_1^{n-1} \Delta T_i = \sum_1^{n-1} V_i^2 \Delta T_i. \tag{11}$$

Subtract equation (11) from (10) to get

$$V_n^2 = \left(V_{A_n}^2 \sum_1^n \Delta T_i - V_{A_{n-1}}^2 \sum_1^{n-1} \Delta T_i \right) / \Delta T_n. \tag{12}$$

This result shows that errors made on earlier and later interfaces have no effect on the nth interval velocity. If, for example, $V_{A(n-2)}^2$ corresponded to a multiple but was included by mistake, this mistake would have no effect on the calculation of V_n. Such errors are not cumulative. One may note also in passing that the necessary and sufficient condition for $V_n = V_{A_n}$ is that $V_{A_n} = V_{A_{n-1}}$.

Correction to Beginnings of Reflections

We have tacitly assumed up to this point that reflection times are minimum travel times from datum level at the source to reflector to datum level at the geophone. This is not correct, as, in practice, we are not able to pick the beginnings of reflections. So we try to make a correction. This correction is clearly a weak point in an otherwise remarkably accurate procedure. However, as we shall see, depths are not very sensitive to errors in timing and interval velocities may in some cases be found with very good accuracy in spite of this difficulty. For other sources of error, see the discussion by Widess (1952). For very careful work the correction for x at the datum ought to be included.

Suppose we work with a good reflection. For each trace we pick each peak and trough. The corresponding T_x's are squared and plotted against x^2. We then have a series of V_A^2's for this reflection. We can get an idea of the variation of V_A^2 with T_0. Our interest is in limiting values of V_A^2 and T_0 as we approach the beginning of the reflection.

Now we may look at the problem from another viewpoint, making the hypothesis that the shape (or character) of the pulse does not change with x. Then if the first reflection is being picked at T_x, we estimate this time is δ too large. Then the corrected V_A^2 will be

$$(V_A)_\delta^2 = x^2/\{(T_x - \delta)^2 - (T_0 + \delta)^2\} \approx V_A^2(1 + \delta/T_0). \tag{13}$$

So the hypothesis of unchanging shape is equivalent to the supposition that V_A^2 depends linearly on δ (measured say near $x=0$). Whether or not this hypothesis is correct can be determined by picking all peaks and troughs and plotting as outlined in the preceding paragraph. Usually the deviations from the hypothesis of uniformity of shape do not appear to be significant, so we use this hypothesis. Its use should be restricted to a limited range of angles of incidence near zero, as otherwise it simply is not correct.

Notice in equation (13) that the effect of the δ-correction is always to increase $(V_A)_\delta$. We find then that, for example,

$$\begin{aligned}(\Delta z_1)_\delta &= (V_A)_\delta(\Delta T_1 - \delta)/2 = V_A(1 + \delta/\Delta T_1)^{1/2}(1 - \delta/\Delta T_1)\Delta T_1/2 \\ &\approx \Delta z_1(1 - \delta/2T_0).\end{aligned} \tag{14}$$

Thus the corrected depth differs from the uncorrected depth by half as much as it would if the V_A^2 had not been influenced by the correction. If we extract the square root of both sides of (13) we find that the velocity also is changed by the same percentage but in the opposite direction. The factor $1/2$ which occurs in both corrections removes some of the damage done by the uncertainty of δ but not enough in case the reflections are very good.

In case the reflections are very good it may be worth while to measure the variation of V_A^2 by the direct method outlined above, since deviations from the hypothesis of uniformity of shape with x usually appear to be in the direction of minimizing still further any errors in Δz due to uncertainties in δ.

Relative Corrections and Interval Velocities

The situation here is not nearly so bad as it was in the last section. Here we have again to deal with corrections to the beginning of reflections. But now our corrections must be applied to two successive reflections and our primary interest is to minimize the relative errors in these corrections.

Referring to (12), if the actual correction made is δ_i and the true correction δ_i^T and $\Delta_i = \delta_i^T - \delta_i$ for the ith reflection then let us compare the true squared interval velocity, $(V_n^T)^2$ with the corrected squared interval velocity, $(V_n)^2$.

After some reductions we find

$$(V_n T)^2 \approx (V_n)^2(1 + (\Delta_n - \Delta_{n-1})/\Delta T_n). \quad (15)$$

Thus the percentage error is measured by $(\Delta_n - \Delta_{n-1})/\Delta T_n$. ΔT_n is the vertical interval reflection time between reflectors and is usually not very large, perhaps of the order of 0.1 second. When the $(n-1)$st and nth reflections are good enough so that corresponding phases of them can be accurately matched, then $\Delta_n - \Delta_{n-1}$ can be reduced to something like 0.005 second. Then in such a case the error in measuring V_n^2 would be about 5% and that in measuring V_n would be about 2.5% The reader will remember that this estimate of accuracy is made assuming ideal conditions of plane non-dipping reflectors bounding homogeneous strata. The accuracy could not be as good as 2.5% in an actual case.

But one is easily led by these considerations to hope that even when $\Delta T_n \approx 0.025$ second, if $\Delta_n - \Delta_{n-1}$ can be kept down to 0.005 second, the error in V_n will be ideally 10% and practically less than, say, 20%. However this hope must not prevent a strictly objective assessment of the range of uncertainty at the end of the work.

It may come as a shock to some that 20% accuracy is regarded as good. Remember, however, that 0.025 seconds time interval is very small—it corresponds to an interval of the order of 100 feet thick. In ordinary well shooting for velocities, comparable accuracy can be achieved only with comparable care. With more recent sonic logging techniques much greater accuracy can be expected. Remember, we make the assumption that no well is available.

In the struggle to minimize $\Delta_n - \Delta_{n-1}$, every device that will improve accuracy should be used. Basically what is wanted is to determine the shape of the recorded signal pulse. I usually try to do this by tracing this shape as best I can on a piece of transparent plastic. I try to average out noise effects as much as possible. This somewhat unsatisfactory operation can be much improved by adjusting times for shallow irregularities and also for regular changes due to variation of angle of incidence and to dip (if present) and then averaging (or mixing). This is the type of operation that has been so fruitful in studying daily variations of the earth's magnetic field. A reproducible recording mechanism is clearly very useful in such an operation. However, if the interpreter has some understanding of the characteristics of his instruments and the reflections are reasonably good, with very few oscillations (obtained by using a minimum of filtering), the tracing procedure is usually sufficient to permit one to identify positive and negative (relatively speaking only) reflections and so make a fairly accurate correlation of common phase positions on adjacent reflections. In this one must try to extract from the data a maximum of extractable information.

When one has made such a study, one must then confront the positive, negative sequence with the interval velocity sequence. If the densities do not change appreciably in successive layers, then a negative reflection must correspond to a decrease of velocity and a positive to an increase of velocity with increasing depth.

From this one can usually determine the absolute signs of the reflections. When an inconsistency remains, one then has to appeal to the fact that the sign of the reflection depends, not on V, but on ρV, the product of the density and velocity. Reasonable variations of density must of course be permitted.

Multiple Reflections

Any multiple reflections which are present will of course be first picked and interpreted as if they were not multiples. This will often lead to an absurd result when equation (12) is applied blindly. When an absurd result is obtained, the first order of business is to search for the cause. If care has been used to eliminate various disturbing effects, then the two most probable causes of trouble are usually (1) mistakes in calculation and (2) multiples. Clearly (1) must be first eliminated as a possibility before (2) can be very seriously considered.

Although every reflector produces multiples, except in very unusual cases of focusing, the multiples that are easily picked are those involving a reflection from either the ground-to-air interface and/or the interface between the low velocity weathering and the higher velocity layer below. The ground-to-air interface reflects nearly 100% of the energy coming up to it. It is not unusual for the base of the low velocity to reflect 50% of the pulse coming up to it. Therefore we would expect one or both of these shallow interfaces to be involved.

Some of the more probable multiple possibilities are indicated in Figure 5 Cases (c), (d), (g) and (k) correspond to what we shall refer to as *simple multiples*. More specifically, these cases correspond to *simple doubles*. Among the simple doubles (c), (d), and (k) involve two extra paths through the low-velocity weathered layer. Cases (a), (b), and (l) involve an initial upward propagation. But (a) and (b) differ by the time from shot up to base of the low-velocity layer counted only once.

It will be clear that among the doubles one may expect types (a) or (b) to be stronger than types (c) or (g). Types (b) and (i) are to be classed along with (a). Types (e) and (f) are equivalent as far as times are concerned but may be different with respect to pulse shape details. Types (e) and (f) should be intermediate in strength between (c) and (d).

In cases (j) through (m) a shallow reflector not detected as a single is shown at (S) to (S′). Such a failure to detect a shallow reflector occurs quite frequently because these are not usually regarded as having any interest. However, for velocity profiling it is very necessary to try to detect such reflectors. This requires shooting a small charge at the center shot—often only a cap. Sometimes a hidden shallow good reflector can be inferred from the velocity profile. The great danger to the interpretation due to such multiples is that (k), since it comes in so early on the record may not even be suspected of being a multiple. It is difficult to guard against this kind of error except by getting the single from (S) (S′).

In interpreting multiples the shape or character plays a major part. For any reasonably small range of times, about all we can hope to be able to detect is the

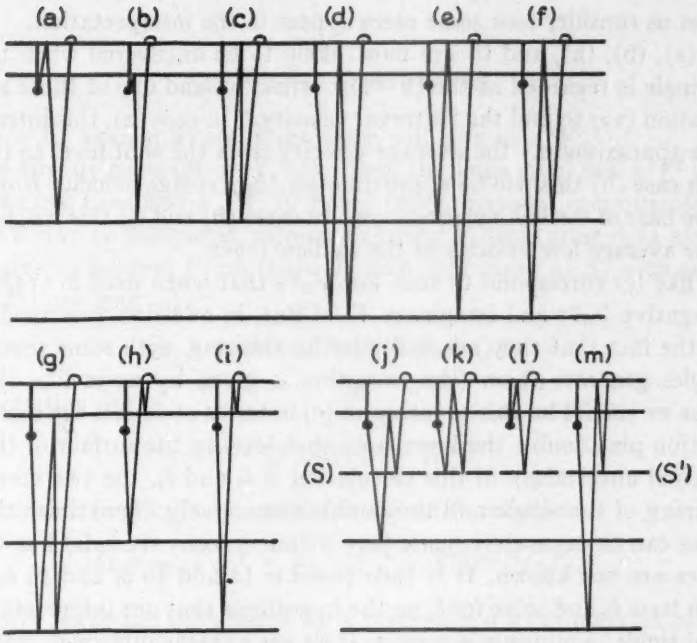

FIG. 5. Various multiple-reflection paths.

sign + or −. But we must be able to make this analysis—otherwise we have to make a series of alternative hypotheses and select the hypothesis least in conflict with the other related interpretive results. Such an elimination process must be carried out where weak reflections are involved, as is quite often the case with multiples.

One characteristic of simple doubles is that they are always negative. This useful fact may help in making an analysis where the sign is otherwise difficult to fix.

A characteristic of multiples involving initial upward propagation (as (a), (b), and (l)) is that they are sensitive to shot depth and are usually most reliably detected by means of this. An otherwise difficult separation of (a) and (b) may be made on this basis.

If the multiple is made by a reflection at the ground-air interface, two passages through the low-velocity weathering are involved. Thus double the layer above datum is added and this influences V_A^2. A time correction along rays must be made. But this correction supposes the validity of geometrical optical principles which are known to be only very roughly valid. Such a correction has to be smoothed or the weathering irregularities, being doubled, will introduce more irregularity than can be allowed to exist. These irregularities are certainly introduced in the double passage through the weathering but they are to a great extent smoothed out physically in the subsequent downward and upward propagation processes.

Now let us consider how some cases appear in the interpretation.

Cases (a), (b), (h), and (i) are most likely to be uncovered when the corresponding single is regarded as the $(n-1)$st reflection and one of these as the nth, using equation (12) to find the "interval velocity." In case (a), this interval velocity will be approximately the average velocity from the shot level to the ground surface. In case (b) this will be approximately the average velocity from the shot level to the base of the low-velocity layer. In cases (h) and (i) this will be approximately the average low velocity of the shallow layer.

Cases like (c) correspond to such low V_A^2's that when used in (12) they may lead to negative V_n^2's and imaginary V_n's! But, in addition, one should be able to verify the fact that they are multiples by showing, with some precision, just what singles generate them (the exception is given by cases like (j) through (m)). Thus we should be able to interpret (c) in terms of double the corresponding single section plus double the layer from shot level to the surface of the ground. The principal uncertainty in this calculation is δ_1 and δ_2, the two corrections to the beginning of the single and the double respectively. Sometimes the relative corrections can be accurately made (say within ± 0.005 seconds) but their absolute values are not known. It is then possible to add to δ_1 and to δ_2 the same correction term δ_c and solve for δ_c on the hypothesis that our interpretation of the relation of single to multiple is correct. If we get a reasonably small (say less than ± 0.020 seconds) value for δ_c in this way, we may regard $\delta_1+\delta_c$ and $\delta_2+\delta_c$ as probably closer than δ_1 and δ_2 as the absolute (approximate) corrections to the reflection beginning.

The study of the multiples can thus be turned to give more information about the singles and so instead of being a nuisance may be converted into a useful tool. This optimistic statement cannot be made in many cases because disturbing factors are too strong to permit such a sharp view of the situation. However, this fact need not prevent very accurate interpretations where the records do permit such results.

DISTURBING EFFECTS

Thus far we have supposed no dip, no curvature, homogeneous layers—that is, the simplest ideal situations. Some disturbing factors can be taken into account and their effects reduced. Methods of attacking such problems are now considered.

Dip

A correction for dip has been given by Gardner (1947) which is directly applicable to our case also. He does not give the derivation so I supply it below. In triangle $S_I S_{II} S_I'$ (Figure 6) note that

$$\begin{aligned}(S_{II}S_I')^2 = V^2T_x^2 &= x^2 + (S_IS_I')^2 + 2x(S_IS_I')\sin\theta \\ &= x^2 + V^2T_0^2 + x^2\sin^2\theta - 2VT_0x\sin\theta + 2VT_0x\sin\theta - 2x^2\sin^2\theta \\ &= V^2T_0^2 + x^2\cos^2\theta\end{aligned}$$

or

$$T_x^2 = T_0^2 + (\cos^2\theta/V^2)x^2. \tag{16}$$

So if we plot T_x^2 against $x^2\cos^2\theta$ the slope will give us $1/V^2$.

Or if we already have the x^2, T_x^2 plot then the slope gives $\cos^2\theta/V^2$ and if we can find θ we can then find V. M. B. Favre (1953, personal communication) has shown how θ may be computed without knowing V, from time data alone. This result one gets as follows. From the split with shot point at S_0 with geophones from S_I to S_{II} one gets

$$\sin\theta = (V/x)(T_{0II}^2 - T_{0I}^2)/2T_0 \tag{17}$$

and from equation (16),

$$\cos\theta = (V/x)(T_x^2 - T_0^2)^{1/2}. \tag{18}$$

Dividing equation (17) by (18) one obtains Favre's relation

$$\tan\theta = (T_{0II}^2 - T_{0I}^2)(T_x^2 - T_0^2)^{-1/2}/2T_0. \tag{19}$$

I had formerly made the calculation by a successive approximations procedure. For the first approximation let $\theta=0$ and calculate $(V)_1$ from the slope of the x^2-T_x^2 graph. Then using $(V)_1$ calculate $(\theta)_2$ (the second approximation to θ) from the approximation to (17)

$$\sin(\theta)_2 \approx (V)_1\Delta T/x. \tag{20}$$

Then $(V)_2=(V)_1\cos(\theta)_2$ gives the second approximation to V. And so on. Usually the second approximation is good enough. But Favre's formula or its approximate expression

$$\tan\theta \approx \Delta T(T_x^2 - T_0^2)^{-1/2}, \tag{21}$$

is better.

The above considerations apply strictly only to one layer. For the second layer we have the ΔT of the second reflection at S.P. 0 which gives, in the plane of the survey, the direction of the ray issuing from and returning to S_0. The generalization to three dimensions can also be carried through (Dix and Lawlor, 1943; Dürbaum, 1953). The calculation made with reference to Figure 4 above is really a calculation to determine the limiting radius of curvature of the symmetric x-T_x graph at $x=0$ ("symmetric" refers here to the symmetry of S_I and S_{II} with respect to S_0 in Figure 6 and the symmetry is not exact but only is true to first order in x). We can thus compute the removal of the first layer and the problem is reduced to that of computing the second layer. For the finite case it is good to have regular continuous-profile data along the line of the survey because this permits shifting of the center time to its proper position of symmetry in the second layer.

The above outline applies to any number of layers. I shall not clutter the paper with the slightly painful details.

However, the special case in which the reflecting interfaces are all parallel is especially simple and also somewhat important so we look at it briefly here.

Refer to Figures 7 and 4. To first order in $x(=x_1+x_2)$, if we add to T_{xR} (means T_x shot toward right) the time $x \sin\theta/V_1$ and use $x\cos\theta$ in place of x we reduce the problem to the zero dip problem excepting that we have lost our symmetry. Using the same x and shooting toward the left (not shown), we have to replace x by $x\cos\theta$ and T_{xL} (means T_x shot toward left) by $T_{xL}-x\sin\theta/V_1$. We again get a reduction to the case of Figure 4 but without symmetry. By averaging these two

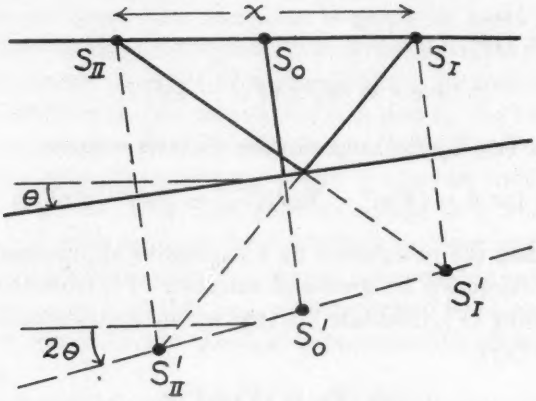

FIG. 6. Geometrical arrangement used for calculation of the dip correction when the distance from shot to geophone increases symmetrically about a center point, S_0.

cases we again get symmetry. In this way we see that equation (16) may be applied to all reflections. But x does not appear in equation (9), so $x\cos\theta$ does not appear there also (actually the effect of θ is only hidden in V_1). Thus if V_1 is properly computed, (9) and (12) may be used for the other layers just as they stand if the other reflectors are parallel to the first.

The process I have used in the general case (starting with the second layer problem) is to assume parallelism of the first and second reflectors as a first approximation. Using this first approximation to the velocity (in the second layer) and the split ΔT for the second reflector, then calculate the first approximation to the angle between the first and second reflector. With this angle the reduced problem for the second layer can be made symmetric so that Gardner's relation (16) may be applied to compute a second approximation to the velocity. This process is continued until further changes, with successive steps, of V_2 and the angle between the first and second reflectors become negligible.

The procedure outlined in the above paragraph is clearly applicable to any number of layers.

It may be interesting to note that in a regular continuous profile a type of cor-

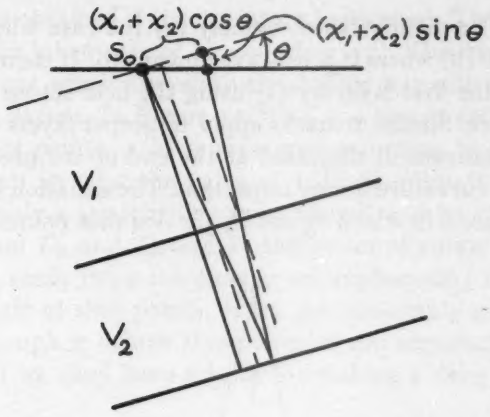

FIG. 7. Geometry needed to handle case of parallel dip with arbitrarily small distance from shot to geophone, x_1+x_2.

rection for shallow velocity variations is often useful. For example, in parts of Canada it is useful to use an especially deep datum because important velocity variations exist in the relatively shallow layers that are below the ordinary low-velocity layer. The field set-up is shown in Figure 8. From the figure one may

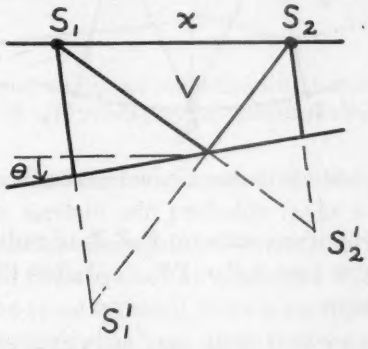

FIG. 8. Shot-to-shot tie over a plane dipping reflector.

show that if T_{01} and T_{02} are the times from shot points S_1 and S_2 for zero geophone distance (corrected to a shallow datum) and T_x is the time from S_1 to S_2 a distance x apart, then

$$V^2 = x^2/(T_x^2 - T_{01}\,T_{02}) \qquad (22)$$

exactly (Pflueger, 1954, p. 339–340). But this formula, which is correct for plane reflectors, is very sensitive to curvature, which we now proceed to consider.

Curvature

The effect of curvature in the general case is most difficult to correct. In practice graphical methods have been used.

Two cases may be distinguished, namely (a) the case where the reflector is concave upward and (b) where it is concave downward. If there are no buried foci the calculation for the first layer by (1) using the field set-up of Figure 1 is not affected by curvature. Similar remarks apply to deeper layers also.

For the field arrangement discussed at the end of the preceding sub-section (Fig. 8) the effect of curvature is very important. The situation may be understood by reference to Figure 9 in which S_1 and S_2 are two shot points, C is the center of

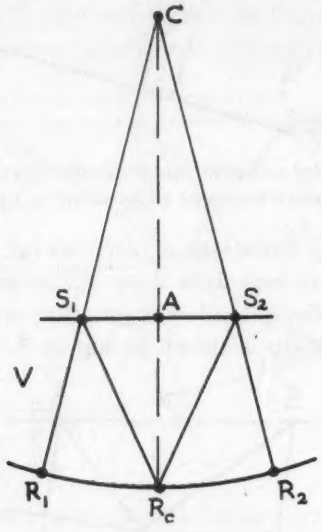

FIG. 9. Shot-to-shot tie over a curved non-dipping reflector.

curvature of a circular cylindrical reflector $R_1R_cR_2$ of radius of curvature $CR_1=\rho$. Let V be the true velocity so that $S_1R_1=VT_{01}/2$, $S_2R_2=VT_{02}/2$ and $S_1R_c=VT_x/2$. So in triangle S_1AC we have

$$(\rho - VT_{01}/2)^2 = x^2/4 + (\rho - AR_c)^2 \tag{23}$$

and in AR_cS_1

$$(AR_c)^2 = (VT_x)^2/4 - x^2/4. \tag{24}$$

If we eliminate AR_c and solve for ρ we get

$$\rho = (V/4)(T_x^2 - T_{01}^2)/[(T_x^2 - x^2/V^2)^{1/2} - T_{01}]. \tag{25}$$

If we write

$$\overline{V}^2 = x^2/(T_x^2 - T_{01}^2) \tag{26}$$

we can rewrite (25) as

$$\rho = (Vx^2/4\overline{V}^2)/[\{T_{01}^2 + x^2(1/\overline{V}^2 - 1/V^2)\}^{1/2} - T_{01}]. \tag{27}$$

The same relation is obtained if the curvature is reversed. The sign of the curvature is automatically taken care of by equation (27). This result is quite useful for making corrections which are relatively shallow but still below the ordinary shallow weathering datum. In Figure 10, $0-S$ is a line of shot points. For each adjacent pair of shot points, $1/\overline{V^2}$ is measured according to equation (26). Between each such pair we plot the value of $1/\overline{V^2}$ as ordinate. Then we draw a smooth curve (possibly a straight line as indicated) and let the smoothed value represent $1/V^2$. From T_{01} and T_{02} and V, the center of curvature is found and ρ is found, so one can easily draw the circular arc representing the average curved reflector for each pair of shot points. If we use reasonably good shallow reflections with large enough x values these circular arc segments will fit together reasonably well and we shall have a basis for making a deep datum correction.

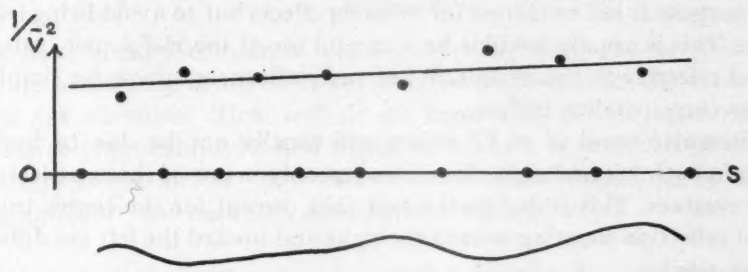

FIG. 10. Cross-section showing continuous profile line with shallow curved reflector and the plot of $1/\overline{V^2}$ points used for curvature calculations.

There are dangers in the blind application of this method. If the shallow reflection is too deep the method will probably make a serious over-correction because of a tendency for diffraction effects to smooth out irregularities that originate at appreciable depth. Clearly also the correction will vary with dip from reflection to reflection on the same spread if there is an appreciable variation of dip.

The objectionable hypothesis has been made that we are dealing with a velocity, V, that is (a) smoothly varying laterally and (b) not variable vertically. Significant failure of either of these conditions may seriously distort the interpretation. My attitude is that, to be very serious, these failures should show in the data. For example, a sudden change in V (laterally) should show in the plot of $1/\overline{V^2}$ as shown in Figure 10. A serious failure of (b) should be expressed in terms of serious incoherence between the deep and shallow interpretations. But if neither of these failures is detectable, then one may suppose that actual deviations are not important. As always, one must look for weak spots in the interpretation and seek an understanding of their causes.

Now we go to a short discussion of the effect of buried foci.

First, how do we detect such effects? The best way seems to be to note first that for a fixed x (distance from shot point to geophone) there are two times,

one corresponding to shooting toward the left and the other corresponding to shooting toward the right. Let these be respectively T_{xL} and T_{xR}. Then we may write $T_x^2 = T_{xL} \cdot T_{xR}$ for each trace distance. As buried foci are more likely to be encountered at larger x's (Dix, 1952, p. 363), we watch the plotted points on the x^2-T_x^2 plot for rather abrupt systematic deviations from an almost straight line. The main reason to plot every trace on the x^2-T_x^2 graph is to detect such effects. Physically, the effect of a buried focal line (Dix, 1952, p. 361–362) is to shift the phase forward for all spectral components of the pulse by 1/4 wave length. But the foci are associated with points on the reflecting surface other than the point of least reflection time and these other points may not be where the curvature of the reflector has buried foci at all. The effect is only rarely clear-cut in field practice, so it may not appear as abruptly as the simple idealized view presented above might indicate.

Our purpose is not to correct for focusing effects but to avoid being led astray by them. This is usually possible by a careful use of the x^2-T_x^2 plot, using every trace and referring to the records. When such influences appear we simply avoid using the corresponding points.

An irregular trend of x^2-T_x^2 points will usually not be due to buried foci shooting in both left and right directions but only in one of these, at least for the smaller x-values. This is due to the fact that, except for the center traces, the points of reflection shooting toward the right and toward the left are different for the same x-value.

Thus far we have referred to curvature effects as if only one layer were involved. If one wishes to correct for effects in deeper layers, then a careful graphical interpretation seems almost necessary. However, an aquaintance with the main tools of geometrical optics has some value. The matter is best studied by regarding the central point of reflection as a source and studying the upward propagation from this point in an axially symmetrical corresponding optical system. These matters are the subject of many treatises and will not be discussed here.

Miscellaneous Disturbing Effects

One of the most important of these is background noise. This may be due to surface waves, interface waves, many small reflections, wind, etc. This noise generally means that times are readable with an accuracy of approximately ± 0.002 second, to cite a fairly frequent practical situation. Thus if $T_x = T_c \pm 0.002$, then $T_x^2 = T_c^2 \pm 0.004 T_c$ so that the scatter on the plot is proportional to T_c. Thus the uncertainty in both the slope and the intercept increases with T_x. The situation is not quite this bad, actually, since for the deeper reflections larger x ranges can usually be used, the main limitation here being associated with the angle of reflection.

Disturbances due to drilling fluids in the weathering, due to "hole fatigue," due to "geophone plant" variation, due to instrumental variations may all be

serious. The first three effects are difficult to account for but may be reduced with special care. The last is a question of good engineering in the instruments. This is usually cared for better in the high frequency range than in the low range. This fact may cause trouble in handling the deeper reflections. One of the best ways to detect this effect is to make an indicial record (Dix, 1952, p. 374–379) and make sure that the indicial responses match on the lower frequency rear end of the recorded pulses as well as in the beginnings. This places a severe requirement on the geophones but not an unduly severe one.

Perhaps the worst disturbing feature is lack of simplicity of geological structure. Clearly a fault or a sudden change of dip or almost any but the most simple undisturbed bedding will cause much trouble. Usually such trouble is easy to see—if at all serious it is likely to render the survey useless.

ACCURACY

We have already considered certain inaccuracies or ranges of uncertainty which are necessarily involved in any measurement system. For each result we have to ask ourselves "How well do we know this—within what range, with what degree of probability?" And whenever we have answered such questions it is necessary to ask further "how reliable are the ideal simplifying hypotheses in the background—the necessary assumptions without which we cannot proceed at all?"

The question of accuracy may be handled directly. Any assemblage of data, e.g., a collection of x^2-T_x^2 points on a graph, may be duplicated, say, by making n prints from an original. Each of these n prints may be handed to each of n competent persons to measure, say, T_0 and V_A^2. We will then get n values for each of these quantities. After eliminating gross mistakes, the extreme range of these quantities can be divided into a not very large number of intervals and the total number of measurements in each interval can be counted and divided by n. These ratios are the frequencies for the various ranges of say T_0 and V_A^2. Each frequency may be plotted. As the measurements tend to cluster, the frequency plot may be approximated by the Gaussian normal error curve given by

$$p(x) = (1/\sigma(2\pi)^{1/2}) \exp(-x^2/2\sigma^2) \tag{28}$$

where σ is the standard error. 2σ is the distance between inflection points on the bell shaped curve. The range from -2σ to $+2\sigma$ is for many of our purposes a good practical measure of certainty—there is about one chance in 20 that a measure will fall outside of this range. So if the n measures of V_A^2 lead to $(V_A)^2 = (9.120 \times 10^6 \pm 0.011 \times 10^6)(m/s)^2$ then we will suppose that V_A^2 has 19 chances out of 20 of being within the range 9.142×10^6 to 9.098×10^6.

The above procedure is very long and cumbersome. A shorter procedure is to apply the method of least squares (Jeffreys, 1939, p. 121–126; Whittaker and Robinson, 1940, chapter 9) to calculate the "best fit" values *and* the range of variation associated with each.

When the standard errors have been computed, one finds the errors of derived quantities by using the so-called "law of propagation of errors" that is discussed in all books on the subject. Or if one wishes, he can use the direct procedure involving repeated calculations throughout the entire study. The great advantage of this latter type of procedure is that in it every quantity that is measured has a clear meaning—the shorter least squares process is sometimes misunderstood.

But when we have made such calculations, what of the validity of the background hypotheses? Is it legitimate to use a straight line to fit the x^2-T_x^2 data? Is it a good enough approximation to assume layers of constant velocity? And there are many other questions of this kind always. Many detailed considerations of the main possible kinds of measurement uncertainties are well presented in the paper by Widess (1952).

The answers to all of these questions must always depend on experience. Even if we can't give precise answers, it is good to ask these questions as it keeps us on guard against the clearly erroneous supposition that our simplifying hypotheses are absolutely correct.

If we are to make geophysical investigations at all we must take chances. The correct language for understanding all such matters is the language of the theory of probability.

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GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 87–103, 7 FIGS.

THE MECHANISM OF GENERATION OF LONG WAVES FROM EXPLOSIONS*

C. HEWITT DIX†

ABSTRACT

Cagniard's method is applied to the numerical calculation of the vertical displacement due to a point source in a semi-infinite elastic solid medium at three points on a vertical line through the source. The source is a step in the scalar displacement potential. From these calculated responses the response for any physically possible spherically symmetric source can be computed by application of the Duhamel integral.

Clear evidence of backward transmission of transverse wave energy is found along the vertical axis through the source. This, together with the energy of the longitudinal waves, also transmitted backwards, accounts for the mechanism by which energy is held near the source and near the free surface long enough to account for the generation of long period surface waves.

This mechanism of generation of long period surface waves is not restricted to the free surface case. Any good reflector, which also generates secondary transverse waves from longitudinal primary waves, will serve the purpose. It is suggested that this gives a clue to the mechanism of the formation of "ground roll" in many practical cases.

INTRODUCTION

For some years I have sought an understanding of the mechanism (Dix, 1952, p. 366–369) by which the energy of an underground explosion is divided into the predominantly high-frequency pulses (our useful signals) and the predominantly low-frequency "surface waves." It has been quite clear for many years that this separation does take place. It is regularly observed even where the weathered layer of low velocity is of negligible thickness.

A long series of theoretical studies (Lamb, 1904; Sakai, 1934; Cagniard, 1939; Fu, 1947) is in general agreement that the phenomenon exists. All of their calculations are based on well established relations of mechanics and the conditions of the particular problem. Although this theoretical work gave correct predictions and so presumably was correct, it gave an end result that was no more illuminating for my understanding of the separation process than the field observations.

An essential purpose of a physical theory is to give means of making predictions of behavior of a physical system which can be verified by observation and experiment. Within the framework of a valid theory one may seek those interrelations giving general properties of the phenomena that make a simple viewpoint of part of the field of inquiry possible. What I seek is a viewpoint from which the separation into high-frequency signal and low-frequency ground roll may be clearly understood.

Some progress has been made in the direction of obtaining a clear, simple viewpoint for understanding the mechanism by which long waves may be generated. The result is, briefly, the following:

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rounding the spherical cavity of radius a, V is the longitudinal wave velocity, r is the radial distance from the center of the cavity to the field point where the displacement potential is to be observed, t is the time, s is the ratio of the Lamé elastic constants λ/μ, $\tau=t-r/V$, $\kappa=2V/\{a(2+s)\}$, and $\gamma=\kappa(1+s)^{1/2}$.

The corresponding radial displacement is

$$\left(\frac{\partial\psi_P}{\partial r}\right)_{\tau>0} = -\frac{\psi_P}{r} + \frac{P_0a^2(2+s)}{2\sigma rV^2(1+s)^{1/2}}e^{-\kappa\tau}\sin\gamma\tau. \tag{2}$$

The dilatation is

$$(\nabla^2\psi_P)_{\tau>0} = -\frac{P_0a}{\sigma rV^2}\left(\frac{2+s}{1+s}\right)^{1/2}e^{-\kappa\tau}\cos\left(\gamma\tau+\tan^{-1}(1+s)^{-1/2}\right). \tag{3}$$

Figures 1, 2, and 3 show these respective quantities for the case $V=2{,}000$ m/s, $a=5$ meters, $\sigma=2$ g/cm^3, $s=1$ and 4 (which correspond respectively to Poisson ratios of 0.25 and 0.4), and $P_0=1$. I suppose $s=4$ may be typical of a wet clay and $s=1$ of a sandstone or limestone. The 5-meter radius is supposed to approximate the average distance from the center of the cavity at which the hypothesis of linear elasticity becomes sufficiently good. It is seen that the period of the oscillation is proportional to the radius of the cavity if the other quantities are held

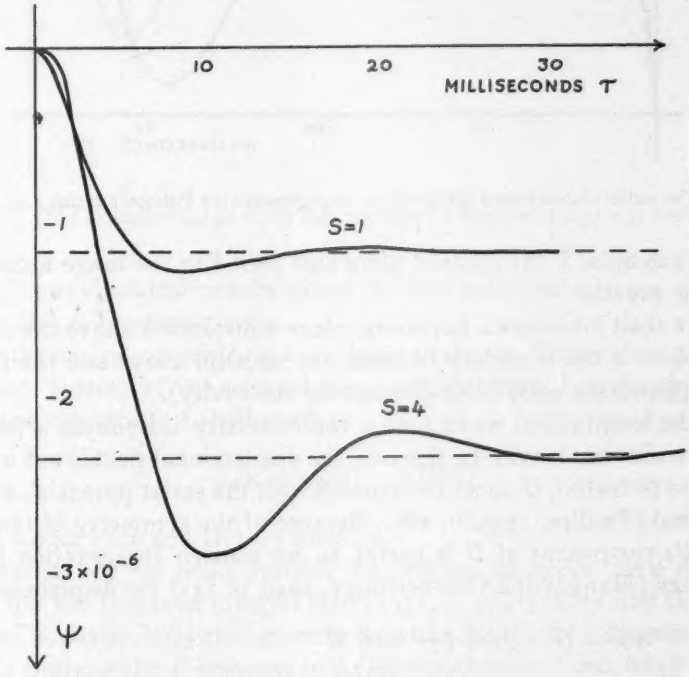

FIG. 1. The displacement potential, ψ, for an input step pressure for Poisson's ratios 0.25 ($s=1$) and 0.4 ($s=4$).

(a) The spreading spherical pulse from the buried source is converted into non-spherical secondary disturbances on striking the free surface;
(b) as a consequence of this non-spherical character, the propagation is no longer simply in the outward direction along rays perpendicular to the reflected pulse fronts, but is generally in every available direction;
(c) an appreciable amount of this energy goes back toward the source or toward a vertical axis through the source;
(d) thus energy is held near the source and near the free surface for a time long compared with the time it takes for energy of the signal to be transmitted away from the source neighborhood; and
(e) this long held energy spreads outward in the available modes, one of which is the surface wave mode of Rayleigh.

In order to verify this result we study the particular case of a source 20 meters beneath the surface and the response on a vertical line through this source at depths of zero, 10, and 40 meters. The real reason this vertical axis was selected is that this was the location where numerical calculations were easiest to carry through. A better reason for selecting this axis is that on it the backward transmission used in (b) and (c) above is most strikingly apparent. The transverse wave contributes appreciably to the vertical displacement. This feature which can only come from backward transmission of transverse waves gives clear verification of the result. This phenomenon has appeared also in other studies (Mencher, 1953; Garvin, 1954; Ginsburg and Roever, 1954; Cagniard, 1939, p. 158).

STATEMENT OF THE PHYSICAL PROBLEM

When an explosion is fired in a buried cavity, the pressure builds up very rapidly. Furthermore, one expects that this pressure will decay rapidly although it will decay less rapidly than it builds up. Consequently, it may be that we can form a rough approximate idea of this process if we consider the pressure to be an ideal step function of time; i.e., it is zero until a certain time and then it suddenly builds up to value P_0 and maintains this value without decay.

Insofar as this idealization may be used and insofar as we can regard the neighborhood of the source as behaving linearly and elastically, we can use the results of several investigators (Kawasumi and Yosiyama, 1935; Sharpe, 1942; Fu, 1945; Menzel, 1951; Blake, 1952) to show the relationship between the potential for the displacement, which we shall call ψ_P and the time, t, when the pressure input is a step function. This relationship is the following:

$$\psi_P(r, t) = 0 \quad \text{for} \quad \tau < 0,$$

$$= \frac{P_0 a^3 (2+s)}{4\sigma r V^2}\left[-1 + \left(\frac{2+s}{1+s}\right)^{1/2} e^{-\kappa\tau}\cos\left(\gamma\tau - \tan^{-1}(1+s)^{-1/2}\right)\right]$$

$$\text{for } \tau > 0, \qquad (1)$$

where P_0 is the height of the pressure step, σ is the density of the material sur-

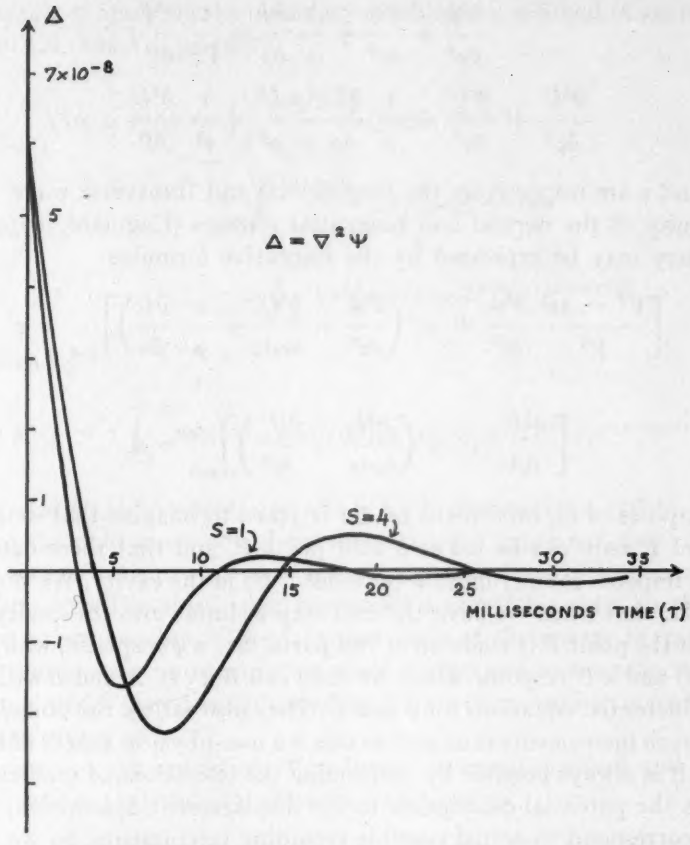

FIG. 3. The dilatation for an input step pressure for Poisson's ratios 0.25 and 0.4.

where (ρ, z) are cylindrical coordinates of the field point and i_ρ, i_z are unit vectors in the ρ, z directions respectively.

For mathematical convenience I am going to change the problem to a slightly different one. Instead of the source being a step pressure, I shall suppose it is a step ψ. More specifically I shall suppose

$$\psi_s(r, t) = 1(t - r/V)/r \tag{5}$$

where $1(\tau) = 0$ for $\tau < 0$ and $1(\tau) = 1$ for $\tau > 0$.

This change will not really restrict the problem as, given the ψ response to ψ_s, we can use the Duhamel integral (Dix, 1952, p. 374–378) to find the response to any input ψ, particularly that given in equation (1) for the step pressure. Similar remarks apply to the U response to ψ_s. Observe however that when the radius of the cavity, a, is very small, ψ_P is approximately a constant times $\dot{\psi}_s$.

The equations of motion (Cagniard, 1939, p. 3–4) are implied by

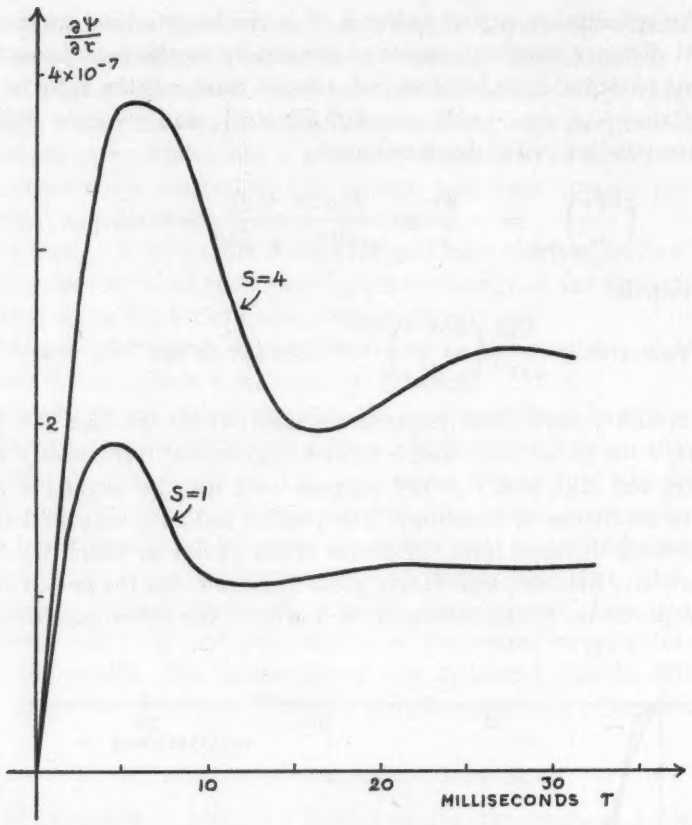

FIG. 2. The radial displacement for an input step pressure for Poisson's ratios 0.25 and 0.4.

fixed. The examples I have picked place this period in the range usually met in prospecting practice.

Next we shall introduce a horizontal plane a distance h above the cavity center. This plane is the boundary between the vacuum above and the homogeneous, isotropic, elastic solid below (except for the cavity).

With the longitudinal wave source the boundary introduces a partial conversion to transverse waves. In this case the displacement field is not irrotational and a vector potential, $\boldsymbol{U}$, must be included with the scalar potential, ψ, to represent this field (Phillips, 1933, p. 186). Because of the symmetry of the problem, only the U_θ component of $\boldsymbol{U}$ is useful, so we shorten the notation by setting $U_\theta = U$. Then (Mangus and Oberhettinger, 1949, p. 145) the displacement vector

$$\begin{aligned} \boldsymbol{u}(\rho, z, t) &= \text{grad } \psi + \text{curl } \boldsymbol{U} \\ &= i_\rho\left(\frac{\partial \psi}{\partial \rho} - \frac{\partial U}{\partial z}\right) + i_z\left(\frac{\partial \psi}{\partial z} + \frac{1}{\rho}\,\frac{\partial(\rho U)}{\partial \rho}\right), \end{aligned} \tag{4}$$

$$\frac{\partial^2\psi}{\partial\rho^2}+\frac{\partial^2\psi}{\partial z^2}+\frac{1}{\rho}\frac{\partial\psi}{\partial\rho}=\frac{1}{V^2}\frac{\partial^2\psi}{\partial t^2} \tag{6}$$

$$\frac{\partial^2U}{\partial\rho^2}+\frac{\partial^2U}{\partial z^2}+\frac{1}{\rho}\frac{\partial U}{\partial\rho}-\frac{U}{\rho^2}=\frac{1}{v^2}\frac{\partial^2U}{\partial t^2}, \tag{7}$$

where V and v are respectively the longitudinal and transverse wave velocities.

Continuity of the normal and tangential stresses (Cagniard, 1939, p. 4) at the boundary may be expressed by the respective formulas

$$\left[\frac{V^2-2v^2}{V^2}\frac{\partial^2\psi}{\partial t^2}+2v^2\left(\frac{\partial^2\psi}{\partial z^2}+\frac{\partial^2U}{\partial\rho\partial z}+\frac{1}{\rho}\frac{\partial U}{\partial z}\right)\right]_{z=0}=0 \tag{8}$$

and

$$\left[\frac{\partial^2U}{\partial t^2}+2v^2\left(\frac{\partial^2\psi}{\partial\rho\partial z}-\frac{\partial^2U}{\partial z^2}\right)\right]_{z=0}=0. \tag{9}$$

For purposes of exposition the reader is asked to imagine that detectors of ψ only and of U only can be set at a field point P, and that these detectors will record the response for any input ψ (or indeed, U) in the cavity. We shall suppose in particular that when we have the unit step ψ_s input into the cavity, then the response at the point P is made up of two parts, *viz.*, a ψ response, which we shall call $A(P, t)$ and a U response which we shall call $B(P, t)$. A and B satisfy the respective differential equations for ψ and U. They also satisfy the boundary conditions. No such instruments exist and so this is a non-physical aspect of the theory. However, it is always possible by performing the operations of gradient and curl to convert the potential description to the displacement description, which can of course correspond to actual possible recording instruments. So we are only a very short distance removed from the physical problem.

What follows now will consist first of calculations of A and B and then of the displacement u_z. When these expressions have been completely evaluated we shall apply them to a special case.

CALCULATION OF u_z AND u_ρ

In this calculation we follow in detail the method used by Cagniard (1939). He makes a Laplace transformation of the entire problem, i.e., the source function, the interface conditions, and the equations of motion. The A is transformed by the relation

$$X(\rho, z, p)=p\int_0^\infty e^{-pt}A(\rho, z, t)dt \tag{10}$$

to X and the B by the relation

$$Y(\rho, z, p)=p\int_0^\infty e^{-pt}B(\rho, z, t)dt \tag{11}$$

to Y. As a result of applying the boundary conditions it is found (Cagniard, 1939, p. 38–42 and 52) that X is given by

$$X(\rho, z, p)/p = \int_0^\infty \frac{udu}{a} J_0(pu\rho)e^{-pa|z-h|}$$

$$- \int_0^\infty \frac{udu}{a} J_0(pu\rho)e^{-pa(z+h)}$$

$$- 2\int_0^\infty bu^3 du J_0(pu\rho)D^{-1}(u)e^{-pa(z+h)} \qquad (12)$$

and Y is given by

$$Y(\rho, z, p)/p = 2\int_0^\infty udu[dJ_0(pu\rho)/d\rho](u^2 + 1/2v^2)D^{-1}(u)e^{-p(ah+bz)} \qquad (13)$$

where $D(u) = (u^2+1/2v^2)^2 - abu^2$, $a = (u^2+1/V^2)^{1/2}$, and $b = (u^2+1/v^2)^{1/2}$. The first two terms of the right-hand side of the formula for X represent, first, the transform of the source (Dix, 1954) and, second, the transform of the image source with negative sign. The third term represents a correction term to this image source which arises because of the fact that some of the energy is transformed in the reflection process into transverse wave energy and so the reflection is not the perfect one which would be indicated by the simple second term on the right, i.e., the image source term.

By carrying out the operations "gradient" on equations (10) and (12) and "curl" on equations (11) and (13) (Garvin, 1954), we get

$$\int_0^\infty e^{-pt} \text{ grad } A dt = \int_0^\infty \frac{udu}{a} \text{ grad } (J_0(pu\rho)e^{-pa|z-h|}) \qquad (14)$$

$$- \int_0^\infty \frac{udu}{a} \text{ grad } (J_0(pu\rho)e^{-pa(z+h)}) \qquad (15)$$

$$- 2\int_0^\infty bu^3 du D^{-1}(u) \text{ grad } (J_0(pu\rho)e^{-pa(z+h)}) \qquad (16)$$

and

$$\int_0^\infty e^{-pt} \text{ curl } B dt$$

$$= \frac{2}{p}\int_0^\infty udu D^{-1}(u)(u^2 + 1/2v^2) \text{ curl } \{[dJ_0(pu\rho)/d\rho]e^{-p(ah+bz)}\}. \qquad (17)$$

First we see that right hand sides (14) and (15) have magnitudes that are respectively

Similarly (Cagniard, 1939, p. 116, equation (16)) as a guide we have from (22) and (23′)

$$2\int_0^\infty udu J_0(pu\rho)g_1(u)e^{-p(ah+az)} = \int_0^\infty e^{-pt}(u_z)_L dt \tag{28}$$

$$2\int_0^\infty udu J_0(pu\rho)g_2(u)e^{-p(ah+bz)} = \int_0^\infty e^{-pt}(u_z)_T dt, \tag{29}$$

where

$$g_1(u) = pabu^2/D(u) = pg_1^*(u) \tag{30}$$

$$g_2(u) = -pu^2(u^2 + 1/2v^2)/D(u) = pg_2^*(u). \tag{31}$$

Let $(u_z)_L^*$ be defined by

$$2\int_0^\infty udu J_0(pu\rho)g_1^*(u)e^{-p(ah+az)} = \int_0^\infty e^{-pt}(u_z)_L^* dt. \tag{32}$$

Then, following Cagniard (1939, Chapter 5; Dix, 1954, equ. (14)–(26)) we have

$$t = i\rho u\cos\omega + ah + az \tag{33}$$

and

$$\left.\begin{aligned}(u_z)_L^* &= 0 \quad \text{for} \quad t < (z+h)/V \\ &= \frac{4}{\pi}\int_0^{\pi/2} \mathcal{R}\{g_1^*(u)u\partial u/\partial t\}\,d\omega \quad \text{for} \quad t > (z+h)/V\end{aligned}\right\}. \tag{34}$$

But the integrand in equation (34) for $\rho = 0$ (see equation (33)) is purely real and independent of ω so

$$((u_z)_L^*)_{t>(z+h)/V} = 2g_1^*(u)u\partial u/\partial t. \tag{35}$$

Differentiating equation (33) with respect to t for $\rho = 0$ gives

$$1 = (z+h)(u/a)(\partial u/\partial t) \tag{36}$$

so equation (35) becomes

$$((u_z)_L^*)_{t>(z+h)/V} = 2ag_1^*(u)/(z+h). \tag{37}$$

Now (Mangus and Oberhettinger, 1949, p. 122) we have

$$2p\int_0^\infty udu J_0(pu\rho)g_1^*(u)e^{-p(ah+az)}$$

$$= \int_0^\infty e^{-pt}\frac{d}{dt}(u_z)_L^* dt + ((u_z)_L^*)_{t=0} = \int_0^\infty e^{-pt}(d(u_z)_L^*/dt)dt$$

$$= \int_0^\infty e^{-pt}(u_z)_L dt \tag{38}$$

$$1(t - r/V)/r^2 + \delta(t - r/V)/rV \tag{18}$$

and

$$1(t - r'/V)/r'^2 + \delta(t - r'/V)/r'V, \tag{19}$$

where δ is the Dirac δ-function. δ is only to be used in an integral combination.

Using equation (4) we see that the remaining displacement components (leaving aside terms from (18) and (19)), (u_ρ) and (u_z), contributed by (16) and (17), are

$$\int_0^\infty e^{-pt}(u_\rho)dt = -2\int_0^\infty bu^3 du D^{-1}(u)\left[dJ_0(pu\rho)/d\rho\right]e^{-pa(z+h)} \tag{20}$$

$$+ 2\int_0^\infty udu(u^2 + 1/2v^2)D^{-1}(u)\left[dJ_0(pu\rho)/d\rho\right]e^{-p(ah+bz)} \tag{21}$$

and

$$\int_0^\infty e^{-pt}(u_z)dt = 2\int_0^\infty bu^3 du D^{-1}(u)J_0(pu\rho)pae^{-pa(z+h)} \tag{22}$$

$$+ \frac{2}{p}\int_0^\infty udu(u^2 + 1/2v^2)D^{-1}(u)$$

$$\cdot\left[\frac{d^2J_0(pu\rho)}{d\rho^2} + \frac{1}{\rho}\frac{dJ_0(pu\rho)}{d\rho}\right]e^{-p(ah+bz)}. \tag{23}$$

Notice that term (23) can be written

$$-2p\int_0^\infty u^3 du(u^2 + 1/2v^2)D^{-1}(u)J_0(pu\rho)e^{-p(ah+bz)}. \tag{23'}$$

The method of Cagniard (1939, Chap. 5; Dix, 1954) may now be used for the inversion of expressions (20), (21), (22), and (23').

Let $(u_p) = (u_p)_L + (u_\rho)_T$ and $(u_z) = (u_z)_L + (u_z)_T$ be the decomposition of (u_p) and (u_z) into longitudinal (with subscript L) and transverse (with subscript T) contributions. Then using Cagniard's process (1939, p. 54, equation (1)) we have from terms (20) and (21)

$$\frac{2}{p}\int_0^\infty udu\,\frac{dJ_0(pu\rho)}{d\rho}f_1(u)e^{-p(ah+az)} = \int_0^\infty e^{-pt}(u_\rho)_L dt \tag{24}$$

$$\frac{2}{p}\int_0^\infty udu\,\frac{dJ_0(pu\rho)}{d\rho}f_2(u)e^{-p(ah+bz)} = \int_0^\infty e^{-pt}(u_\rho)_T dt, \tag{25}$$

where

$$f_1(u) = -pbu^2/D(u) = pf_1^*(u) \tag{26}$$

$$f_2(u) = pb(u^2 + 1/2v^2)/D(u) = pf_2^*(u). \tag{27}$$

and

$$(u_z)_T = \frac{2u^2}{Z^2}\left\{\frac{u^2}{D}\left[f\left\{4(u^2 + 1/2v^2) - \left(u^2\left(\frac{a}{b}+\frac{b}{a}\right) + 2ab\right)\right\} - 2\right]\right.$$
$$\left. - \frac{f}{Z}\left[\frac{hu^3}{a^3} + \frac{zu^3}{b^3} + 2Z\right]\right\}, \qquad (46)$$

where $Z = hu/a + zu/b$ and $f = (u^2 + 1/2v^2)/D(u)$.

NUMERICAL COMPUTATION OF EXAMPLES

We shall take a case of a medium with longitudinal velocity 2,000 m/sec. In all cases the depth of the source is 20 meters. Two cases are described in some detail. First we take a Poisson's ratio of 0.4 (i.e., $s=4$) and $z=10$ meters. The second case will be the same as the first except that $z=0$. Calculations of vertical displacement have been made for $z=0$, 10, and 40 meters and $s=1$ and 4.

Referring to the first case, Figure 4 shows $(u_z)_L$ beginning discontinuously at

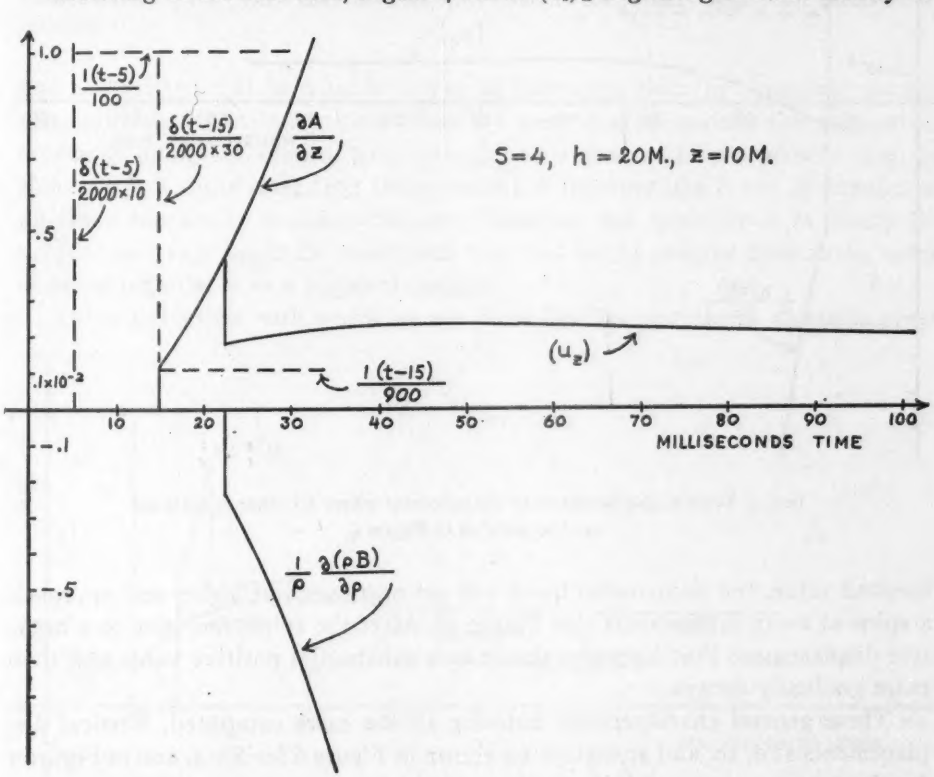

FIG. 4. Vertical displacement at 10 meters below free surface directly above a source of step displacement potential at a depth of 20 meters below surface. The (u_z) curve shows correction to perfect image source reflection. Poisson's ratio is 0.4 ($s=4$). The contribution of the transverse wave appears at 22.25 milliseconds.

since $((u_z)_L^*)_{t=0}=0$. So

$$(u_z)_L = \frac{\partial}{\partial t}(u_z)_L^* = \frac{\partial}{\partial u}(u_z)_L^* \frac{\partial u}{\partial t} = \frac{2}{z+h}\frac{\partial}{\partial u}\left(\frac{a^2bu^2}{D(u)}\right)\frac{\partial u}{\partial t}. \tag{39}$$

In the same way we find the other displacement terms

$$((u_z)_T^*)_{t>h/V+z/v} = 2g_2^*(u)u\partial u/\partial t \tag{40}$$

with

$$t = ah + bz \tag{41}$$

at $\rho=0$. Thus equation (40) becomes

$$((u_z)_T^*)_{t>h/V+z/v} = 2g_2^*(u)/(h/a + z/b). \tag{42}$$

As before

$$(u_z)_T = \frac{\partial}{\partial t}(u_z)_T^* = \frac{\partial}{\partial u}(u_z)_T^*\frac{\partial u}{\partial t} = -2\frac{\partial}{\partial u}\left(\frac{u^2(u^2+1/2v^2)}{D(u)(h/a+z/b)}\right)\frac{\partial u}{\partial t}. \tag{43}$$

One can arrive at equation (39) by differentiation with respect to z of the expression for A, on the $\rho=0$ axis. B can be calculated in the neighborhood of $\rho=0$. Then calculate $(1/\rho)\partial(\rho B)/\partial\rho$ in this neighborhood. This gives equation (43). This very different manipulation serves as a verification of the correctness of equations (39) and (43).

It appeared to me worth while to have this verification by a different procedure as the chance of making a mistake was, for me, not negligible. As important a reason for the two deductions is the somewhat surprising result that $(u_z)_T$ contributes a discontinuous beginning. In some respects this discontinuity is fortunate because it permits a rough model experiment to verify the sudden onset of $(u_z)_T$ on the vertical axis.

Note that for $\rho=0$, $dJ_0(pu\rho)/d\rho=0$, so that the left hand sides of equations (24) and (25) are zero. Consequently

$$(u_\rho)_L = (u_\rho)_T = 0 \tag{44}$$

for $\rho=0$ as clearly must be the case.

By carrying out the indicated differentiation in (39) and (43) we get respectively

$$(u_z)_L = \frac{2}{(z+h)^2D}\left[\frac{a}{D}\left\{(u^2+1/2v^2)^2\left(u^2\left(\frac{a}{b}+\frac{b}{a}\right)+2ab\right)\right.\right.$$
$$\left.\left. - 4abu^2(u^2+1/2v^2)\right\} + abu^2\right] \tag{45}$$

$t = 15$ milliseconds. The $(u_z)_L$ is positive—it increases with t and diverges like t^2.

However at $t = 22.25$ milliseconds the contribution from $(u_z)_T$ first appears and it diverges with t like t^2 and keeps the total vertical displacement finite for all times.

The other example to be considered in some detail is obtained from the one just described by moving the receiver up to the surface where $z = 0$. If we do this gradually, then the 15 and 22.25 millisecond points will move toward the 10 mil-

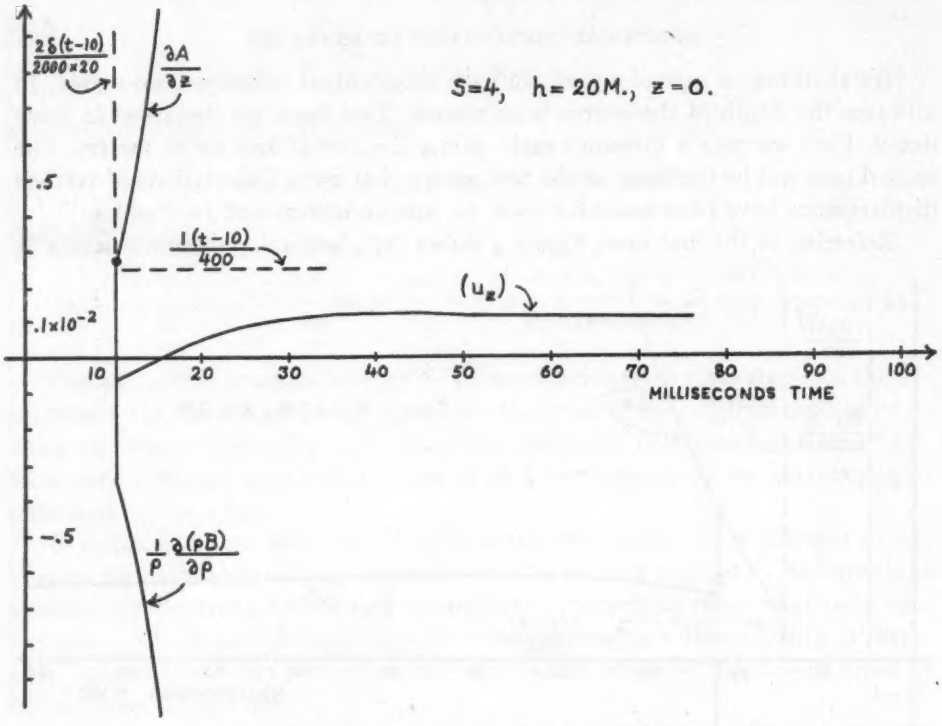

FIG. 5. Vertical displacement at the epicenter where all other conditions are the same as in Figure 4.

lisecond value, the slant-roofed block will get narrower and higher and approach a spine at $t = 10$ milliseconds (see Figure 5). After the spine, one goes to a negative displacement that increases slowly to a substantial positive value and then more gradually decays.

These general characteristics hold for all the cases computed. Vertical displacements at 0, 10, and 40 meters are shown in Figure 6 for $S = 4$, and in Figure 7 for $S = 1$.

A few remarks are in order regarding the diverging character of the longitudinal and transverse wave contributions.

Cagniard has pointed out this divergence effect (Cagniard, 1939, p. 128–133)

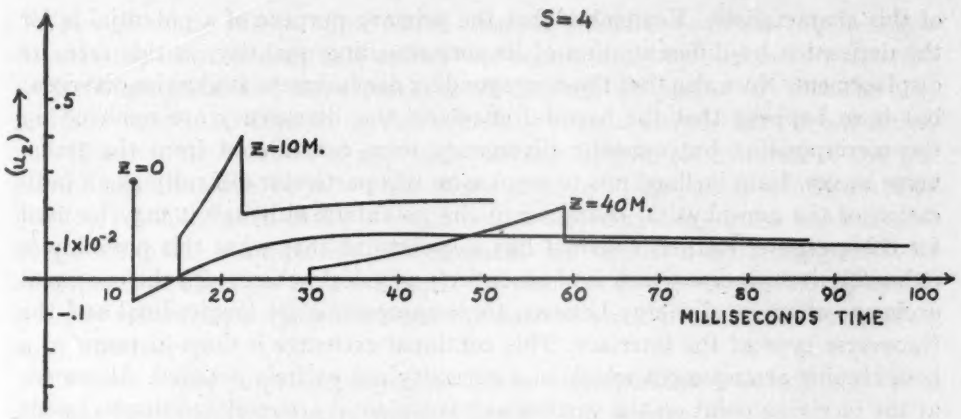

FIG. 6. Vertical displacements at depths zero, ten, and forty meters when the step displacement potential source is twenty meters deep and receivers and source are all on the same vertical line. Poisson's ratio is 0.4 ($s=4$). Only the correction terms to the perfect image point reflection are included.

and has written that he regards this as an indication that the potentials are not physically significant quantities. There is a great deal of merit in this suggestion, especially along the vertical axis through the source, as in the present case. In this case it is quite clear that the potential A diverges like t^2 but B remains at all times identically o along this axis. Therefore the quantity A is clearly divergent and so it might be considered that this would remove from it the merit of being regardable as a physical quantity.

Other potentials with which we are more familiar partake in a certain sense

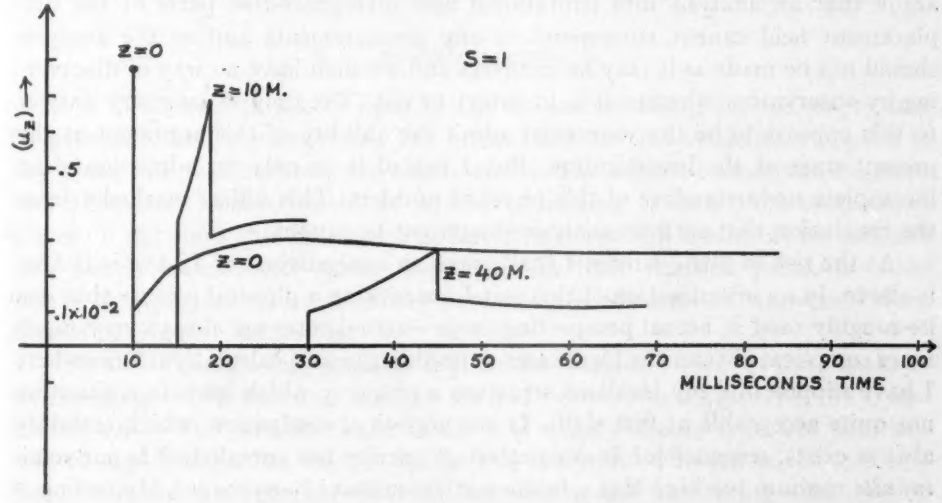

FIG. 7. Same as Figure 6, excepting that Poisson's ratio is 0.25 ($s=1$).

of this characteristic. Remember that the primary purpose of a potential is for the derivation by differentiation of its corresponding quantity, in this case, its displacement. Note also that the corresponding displacement is likewise divergent but it so happens that the harmful effects in this divergency are removed by the corresponding but opposite divergency term contributed from the transverse waves. I am inclined not to emphasize this particular difficulty as an indication of the non-physical character of the potentials although it may be used for this purpose. Rather, I should like to point out that what this probably is indicating is a process which is of an entirely physical nature, *viz.*, the continual exchange of types of energy between the compressional or longitudinal and the transverse type at the interface. This continual exchange is done in terms of a bookkeeping arrangement which is of necessity not entirely detailed. All we see at the receiving point on the vertical axis is the total accumulated displacement contribution up to a given time from an ever-increasing contribution of each type. The energy is not only transmitted from the interface to our point on the vertical axis but it is also transmitted from interior points of the field. The only difference between interior points of the field and the interface in our case is that there is no conversion of type at any interior point of the field. At such interior points, energy which is in the form of longitudinal waves remains that way until it reaches the interface where possible conversion can take place. A simple picture of simple outward transmission of the reflected waves is not adequate. We have to consider transmission in all available directions not only in the interior of the medium but also at the interface.

These divergencies present a troublesome situation to me because they represent an aspect that I feel must be understood but which I do not really understand. It is clearly impossible to measure $(u_z)_L$ independently of $(u_z)_T$. One may argue that an analysis into irrotational and divergence-free parts of the displacement field cannot correspond to any measurements and so the analysis should not be made as it may be incorrect and we shall have no way of discovering by observation whether it is incorrect or not. The only satisfactory answer to this appears to be that one must admit the validity of this argument at the present stage of the investigation. But I regard it as only an admission of an incomplete understanding of this physical problem. This differs markedly from the conclusion that such an analysis should not be sought.

At the risk of being wrong, I shall make an analysis just as I have indicated it above. In an investigation of this sort I am seeking a physical picture that can be roughly used in actual prospecting cases—actual cases are always very much more complicated than the ideal cases amenable to exact calculation. Somewhere I have slipped into my idealized structure a property which leads to a situation not quite acceptable at first sight. Is our neglect of dissipation, which certainly always exists, responsible? Is our neglect of gravity too unrealistic? Is our semi-*infinite* medium too big? Has a mathematical mistake been made? My feeling is that the answers will all turn out to be negative.

The questions can be turned in a different direction—can the requirements (i) that the displacement field satisfy the equations of motion in two separate parts (longitudinal and transverse) for all time and all places, (ii) that the normal and tangential stresses at the boundary remain strictly zero at all times, and (iii) that the solution of any such problem be possible in terms of the Laplace transformation be met without the divergent analysis to which we have been led? Looked at in detail it would not be very surprising if the method used above broke down completely. Requirement (iii) implies a certain regularity of all dependent variables for all time. If for example it were impossible to set up a steady state with a sinusoidal input the method would probably fail (Cagniard, 1939, Chapter 9).

If there is any surprising aspect to this solution perhaps it should only lie in the fact that it can be constructed as Cagniard has shown.

CONCLUSION

It is expected that the reader will secure from the numerical examples presented above the impression that long surface waves generated by impulsive sources of confined character are probably in large part due to backwards transmission associated with conversion of wave type at the interface and to the consequent tendency for long period energy to be delayed and held to a certain extent in the general neighborhood of the source. A conclusion to be reached is that the long-period energy can be minimized by introducing a negative unit step a short time after the positive unit step at the source. Whether this can be done in a practical sense or not is certainly open to question at the present time. This is equivalent to forming the time derivative at the source—not equivalent to a filter unless the instruments and solid medium are very strictly linear.

GENERALIZATION

It is of interest to ask to what extent the mechanism described above may be generalized to any interface. The answer is that this mechanism applies to any plane interface between two elastic media. The reflected waves always show this divergency characteristic. It is also interesting to note that transmitted waves do not show this characteristic but always remain, insofar as we consider only purely transmitted waves, convergent in their separate parts. In other words, the transmitted longitudinal wave and the transmitted transverse wave remain convergent separately.

The above picture may perhaps explain the reason for some of the success of air shooting. When shooting from air we have only to deal first with the transmitted wave. The reflected wave in air is of a very simple type and does not lead to any divergency. Neither do the two transmitted waves at the free surface. However, the reflected wave at the base of the weathering does lead to waves of long period. Since however the source is reasonably far removed from

this base of the weathering in many cases, its contribution of long waves is not very serious.

The air-shooting situation may be compared with shooting in the weathering. In this latter case we have the generation of long waves from two interfaces, the free surface above, and the base of the weathering below. This we may regard as a rather unfortunate situation. It probably accounts in large part for the very high noise level usually encountered in such work.

In certain field problems I have tried to remove or reduce the ground roll, or long surface waves, by deepening the shot. Although this usually works, sometimes it works in the reverse direction! In other words, in rare cases deepening the source appears to increase the amount of surface waves on the record. This has been for me a rather serious mystery for a number of years. If I have correctly pictured the process of generation of these long waves in the above discussion with its present generalization, then I believe I have reached an understanding of this type of anomalous situation. I suppose that the cause of this increase may be either the approach to a strong reflecting interface below the initial shot or possibly the passage through such interface to occupy a shot position between two such interfaces which would give rise to a twofold generation of such long period waves under relatively unfavorable circumstances.

There remains much work to be done on this problem. One would like very much, for example, to make detailed numerical computations of the surface waves at various distances from the epicenter on the surface. This is by no means impossible but it does represent a long detailed numerical computation. It seems a little too difficult to start at the present moment. It is perfectly clear how this calculation is to be carried out since it has been outlined in detail in Cagniard's book (see especially chapters 10, 11, 12, and 13). It may perhaps be carried out by some other group that has larger resources at its disposal than I have.

Another matter of considerable interest that has been left undiscussed is the problem of observational verification of these results. I am convinced that these results can be observed and I would suggest that an interesting place to observe these results would be on a glacier, which presents material of a certain amount of homogeneity over a relatively thick section. Another process is to make the observations in hard rock that is relatively homogeneous. Another possible approach is to use the seismic model techniques that are being currently carried to such a high degree of development.

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GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 104–122, 12 FIGS.

ADDITIONAL NOTES ON THE RESOLVED-TIME COMPUTING METHOD*

R. B. RICE†

ABSTRACT

The basic elements of a time-resolution method of performing reflection seismograph computations have been published previously. The purpose of this paper is to present additional material to show how, by varying the spacing between shot-points on the time cross-section, the method may be made to give results comparable to various standard techniques and to describe the corresponding time method of handling cross-spread data. An additional example showing actual cross-sections computed by the method is included.

INTRODUCTION

In a previous publication (Rice, 1953), the author presented the basic elements of a time-resolution method for performing steep-dip seismic computations. As formulated analytically, the method was based on the non-physically realizable assumption that the ray paths as they appear on the time cross-section are straight lines and are normal to the reflection horizon on this cross-section. This assumption makes possible the graphical resolution of in-line time data by means of a beam compass using the "swinging-arc" method. The details of this graphical resolution and the preparation of the three in-line cross-sections, called the "raw-time," the "resolved-time," and the "depth" sections, were discussed, but no method for handling cross-spread data was included. The main purpose of this paper is to outline a computation procedure for cross spreads. In addition, the important topic of how, by varying the spacing between shotpoints on the resolved-time section, the method may be made to give results comparable to various standard computing techniques is more fully discussed and illustrated.

For convenience of reference, a brief summary of the formulas and graphical procedure for performing in-line computations will be presented first.

SUMMARY OF FORMULAS AND GRAPHICAL PROCEDURE FOR IN-LINE COMPUTATIONS

The "raw-time" section is merely a convenient means of examining the original time data for errors in picking and in computing corrections. It is obtained by plotting the time values (corrected for weathering, elevation, and angularity of path, if necessary) below the shotpoints or midpoints to which they correspond.

In preparing the "resolved-time" section, the shotpoints are spaced on the datum according to a horizontal time t_h, defined by

$$t_h = s/v_h, \tag{1}$$

where s is the distance between the shotpoints and v_h is a variable horizontal

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velocity, which will be discussed later. Using the times from the raw-time section as radii and the shotpoints or midpoints as centers, arcs are swung by means of a beam compass and the reflection horizon is drawn as a series of straight-line segments tangent to these arcs. For portions of the reflection horizon which are concave downward, the segments will be too long and overlap; where the reflection horizon is concave upward, the segments will be too short. Adjustments for these effects of curvature can be made, if desired, after the resolution is complete. It is recommended that if the elevation-correction times are large and the dips are steep, the resolution of the times, corrected only for weathering and angularity of path, should be made from a profile midway between the bottom of the weathered layer and the shot elevations instead of from the datum. This profile is easily obtained on the resolved-time section by plotting elevation-correction times above or below the shotpoints or midpoints to which they correspond on the datum.

The displacements, x_t, and depths, z_t, of the reflection points on the resolved-time section (in time units) are given by the relations:

$$x_t = \tfrac{1}{2}t \sin \alpha_t, \tag{2}$$

$$z_t = \tfrac{1}{2}t \cos \alpha_t, \tag{3}$$

$$\sin \alpha_t = \tfrac{1}{2}\Delta t / t_h, \tag{4}$$

where t is the two-way reflection time, Δt is the two-way stepout time between t and an adjacent time path (with the two path times referred to the same horizontal datum), α_t is the angle of dip of the reflection horizon as it appears on the resolved-time section, and t_h is given by equation (1).

The "depth" section is prepared from the resolved-time section by reading the two-way vertical times between the datum (below which the vertical velocity gradient applies) and the reflection profile below each shotpoint, or midpoint. These times are converted to depth values and plotted below the proper shotpoints, or midpoints, on the depth section, with the shotpoints on this section being spaced according to the distance between them.

Analytically, this is equivalent to multiplying the time displacement x_t by the horizontal velocity v_h, and the "time depth" z_t by the average vertical velocity $\bar{v}(z_t)$, corresponding to z_t, to obtain

$$x = \tfrac{1}{2}v_h t \sin \alpha_t, \tag{5}$$

$$z = \tfrac{1}{2}\bar{v}(z_t)t \cos \alpha_t \tag{6}$$

as the expressions for the horizontal displacement and depth, respectively, of the reflection point.

The formula for the true angle of dip α, as it appears on the depth section, is:

$$\tan \alpha = \Delta z / \Delta x, \tag{7}$$

where

$$\Delta z = z - z' \tag{8}$$

and

$$\Delta x = s + x' - x. \tag{9}$$

In these expressions, x, x' and z, z' denote the offsets and depths, respectively, of two points of reflection corresponding to two points on the datum which are a distance s feet apart.

Note that no restriction is placed on the velocity function used to convert vertical times on the resolved-time section to depths. It may be empirical or analytic, may be assumed to apply below a sloping datum or below the bottom of the weathered layer if one so desires, or may be assumed to vary laterally to compensate for regional trends. Furthermore, as additional velocity information is obtained in an area, new depth sections can easily be prepared from the resolved-time section. In fact, since all features of interest can be detected as well

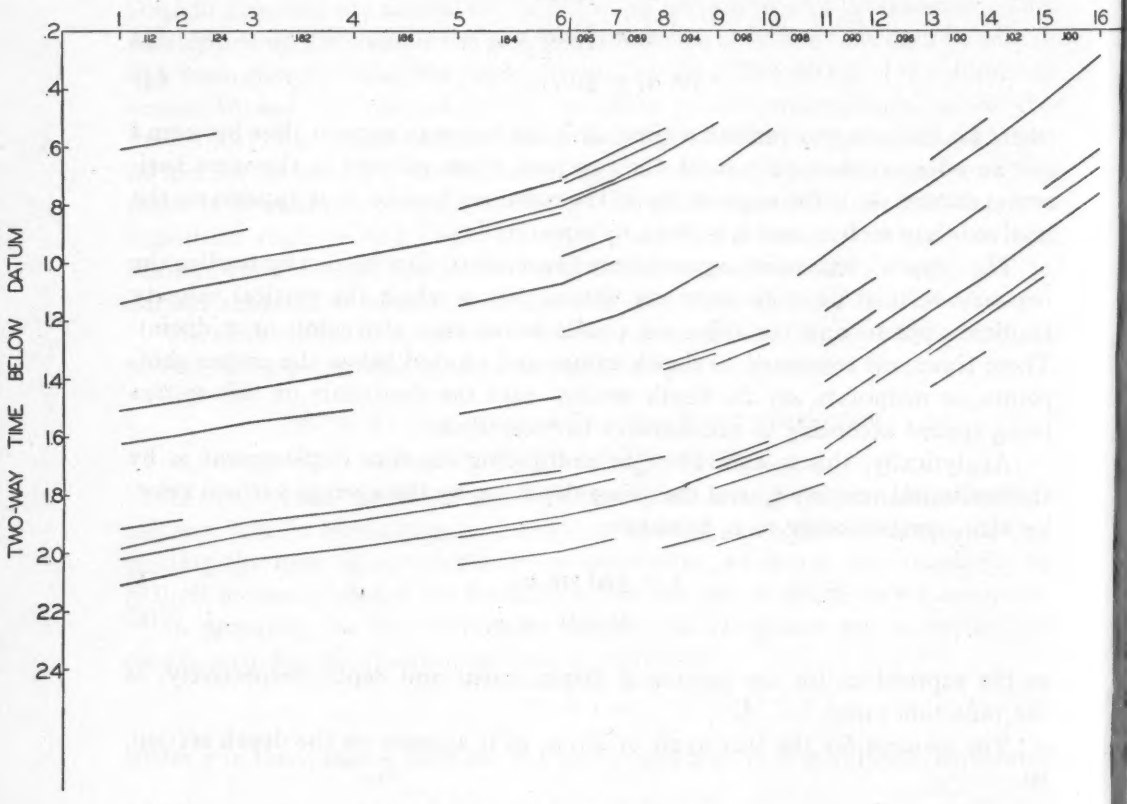

FIG. 1. Example 1. Raw-time section.

from the resolved-time section as from the depth section, the computation of the final depth section may not be justified in new areas where no accurate velocity information is available.

Example

One illustration of the effectiveness of the resolved-time method in defining features such as unconformities, faults, and overturns was presented in the previous paper. Cross-sections for another actual seismic profile of a different type are shown in Figures 1, 2, and 3.

Figure 1 shows the raw-time section for this example. Although the spacing between shotpoints on the raw-time section is arbitrary, in this case the shotpoints have been spaced according to values of t_h (equation (1)), determined by using the first-break refraction velocity for v_h. These horizontal times correspond to either 1,320- or 660-foot spreads, but they vary considerably because the first-break refraction velocities range from 6,500 to 11,800 ft/sec.

Figure 2 shows the corresponding resolved-time section, with the same horizontal time spacing between shotpoints as used on the raw-time section. The times have been resolved from points along the profile midway between the bottom of the weathered layer and the shot elevations as shown. The broken lines

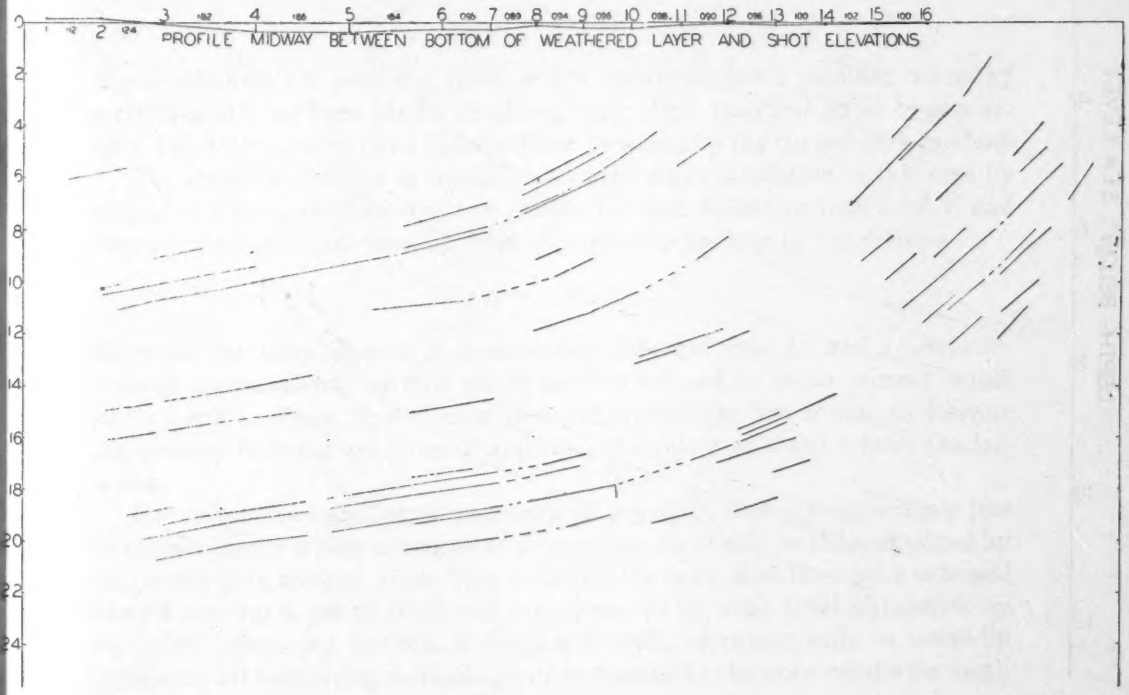

FIG. 2. Example 1. Resolved-time section.

indicate places where the straight-line segments drawn tangent to the arcs were too short because the reflection horizons are concave upward.

When the vertical times between the datum and the reflection horizons in Figure 2 are converted to depth values below sea level and are plotted below the appropriate points (with the shotpoints spaced according to the distances between them), the depth section shown in Figure 3 is the result. The use of sea level as a reference for all depths has been found to be quite convenient for quickly comparing horizon depths over large areas.

This example is a good illustration of the effectiveness of the resolved-time method in producing an accurate resolution of steep dips close to the surface. The shallow steeply-dipping horizons on the right-hand side of Figure 3 actually correlate extremely well, both in dip and displacement, with outcrops in this area. The use of the first-break refraction velocity for v_h explains the good agree-

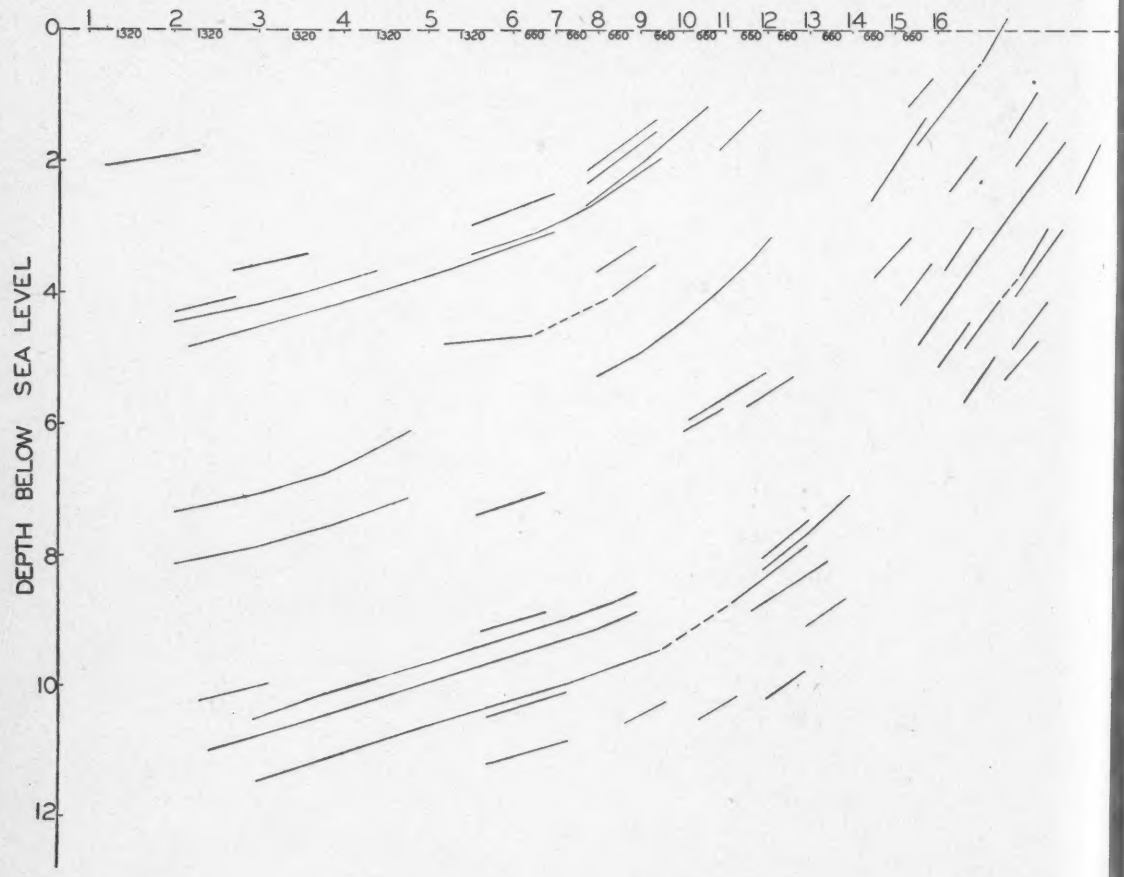

FIG. 3. Example 1. Depth section.

ment. If a larger velocity had been used, the steep dips close to the surface would have migrated too far and would have appeared to be above the surface of the ground.

CHOICE OF HORIZONTAL VELOCITY

Further consideration will now be given to the choice of the horizontal velocity v_h, which determines the spacing of the shotpoints on the resolved-time section and very markedly affects the results. As may be seen from equations (1) through (9), α_t and hence x_t, z_t, x, z, and α all depend directly on v_h. By making v_h small, for a given t, Δt and s, α and x can be made relatively small and z relatively large, or by making v_h large, α and x can be made large and z small.

Variable v_h

One way of handling v_h is to make it vary with z_t. In particular, if we let it be equal to the average vertical velocity, $\bar{v}$, corresponding to z_t, then replacement of v_h by $\bar{v}$ in equations (1) and (5) and substitution of equation (1) in (4) gives, along with equation (6):

$$x = \tfrac{1}{2}\bar{v}t \sin \alpha_t,$$

$$z = \tfrac{1}{2}\bar{v}t \cos \alpha_t,$$

$$\sin \alpha_t = \tfrac{1}{2}\bar{v}\Delta t/s.$$

These relations are precisely those which define Stulken's modified wave-ray method which has been shown (Stulken, 1945; Rice, 1949 and 1950) to give results which are usually quite close to those obtained by the curved-path method.

The graphical method of resolution could be made applicable to this case by preparing a separate resolved-time section for each reflection time level z_t and varying the horizontal time between shotpoints according to the relation

$$t_h = s/\bar{v}(z_t).$$

However, for steep dips, z_t is considerably different from $\frac{1}{2}t$, and a trial-and-error or approximation method would have to be used to obtain correct values for $\bar{v}(z_t)$ and t_h. Hence, in such cases it would probably be just as easy to describe the velocity function analytically and compute values of x and z from the formulas.

But it has not been found necessary to introduce such a complication just to achieve results which are equal to or approximate closely to those obtained by the curved-path method. It has been found that in most cases the results obtained *using a constant* v_h are as good, and sometimes better, than those obtainable by any other computing method. Reference is made, of course, only to steep-dip areas since all computing methods produce essentially the same results for small angles of dip.

Constant v_h

As indicated in the above example, one way of choosing v_h is to set it equal to the first-break refraction velocity below the bottom of the weathered layer. This has been done over wide areas throughout the Mid-continent area and, on the whole, the procedure has given excellent results. Although theoretically it appears that this velocity should not migrate the deeper steep dips far enough, our experience does not bear out this thesis. There are cases, of course, in which more accurate results can be obtained by putting v_h equal to the average vertical velocity corresponding to, say, the middle band of reflections being mapped in order to approximate the case of a variable v_h. On the other hand, in some areas in which the velocity of the first-arrival energy is that of a high-speed bed underlain by beds of lower velocity, a value of v_h lower than the first-break velocity must be selected in order to keep steeply dipping segments from being displaced too far.

Equation of Ray Path for Constant v_h

The equation of the ray path for constant v_h and for a vertical velocity function of the type

$$v = v_0 + A\tau, \tag{10}$$

where v is the instantaneous velocity, v_0 is the initial velocity, A is a constant, and τ is the one-way vertical time, can be easily derived. This is the well-known linear increase of velocity with time which gives a parabolic increase of velocity with depth and produces cycloidal curved paths under the assumption of Snell's law. The average velocity $\bar{v}$ corresponding to v is

$$\bar{v} = v_0 + \tfrac{1}{2}A\tau, \tag{11}$$

which, for the resolved-time method, becomes

$$\bar{v} = v_0 + \tfrac{1}{2}At \cos \alpha_t, \tag{12}$$

since $\tau = z_t$. Putting equation (12) into equation (6) and eliminating t between (5) and (6), one obtains

$$z = (v_0 x/v_h) \cot \alpha_t + (Ax^2/2v_h^2) \cot^2 \alpha_t$$

as the equation of the ray path. Completing the square to put the equation into standard form gives

$$[x + (1/A)v_0 v_h \tan \alpha_t]^2 = (2/A)v_h^2 \tan^2 \alpha_t (z + v_0^2/2A). \tag{13}$$

This is the equation of a parabola opening downward (in the direction of positive z) with vertex at

$$-(1/A)v_0 v_h \tan \alpha_t, \; -v_0^2/2A$$

and with a semi-latus rectum of length $v_h^2 \tan^2 \alpha_t/A$. Note that for $\Delta t = \alpha_t = 0$, the parabola of equation (13) degenerates to the straight line $x = 0$. When

$\alpha_t = \pm 90°$, it becomes infinitely wide and the ray path degenerates to the straight line $z = 0$.

The form of this ray path is admittedly quite unorthodox, but since the ray path is not normal to the reflection horizon on the depth section, its form has very little to do with the results obtained.

Examples to Show Effect of v_h on Results

As an illustration of the different values of horizontal displacement and depth that are obtained using various constant values of v_h, consider Figures 4, 5, and 6 in which resolved-time values for $v_h = 8{,}000$, 9,000, and 10,000 ft/sec, respectively, are compared with curved-path values. The velocity function used is of the form of equation (10), namely,

$$v = 8 + 2.74\tau, \tag{14}$$

where v and v_0 are in thousands of ft/sec.

In Figure 4, results obtained by the resolved-time method when v_h is set equal to the initial velocity, v_0, are shown. In this case, values of x are consistently less and z values greater than the corresponding curved-path results for $\Delta t/s$ values larger than zero. (In Figures 4, 5, and 6, x, z, and s values are all expressed in thousands of feet. Thus, for s equal to 1,000 ft, a $\Delta t/s$ value of 0.04 represents a Δt of 0.04 sec.)

In Figure 5, results are shown for the more realistic case where v_h (9,000 ft/sec) is 12.5 percent greater than v_0. In this case, for reflection times up to 2.4 sec and for $\Delta t/s$ values up to 0.16, resolved-time values are in fairly good agreement with curved-path results. For larger reflection times, the resolved-time method generally produces smaller displacements and larger depths than the curved-path method.

When v_h is made 25 percent greater than v_0 (10,000 ft/sec), Figure 6 shows that displacements are generally larger and depths smaller than curved-path values. The differences are not large, however, for moderate stepout times.

If a faster velocity function had been used, the agreement between the two methods would have been best for some value of v_h larger than 9,000 ft/sec.

Figure 7 shows a comparison of results obtained when the two methods are applied to the overall computation of an asymmetric structural profile. The same velocity function equation, (14), was used. In this example, the two-way reflection times range from 1.35 to 2.60 sec and the two-way stepout times from 0 to .146 sec, the distance between shotpoints being 1,000 ft. Here it is evident that the the best agreement between the two profiles would have been obtained using a v_h of about 9,500 ft/sec.

Figure 8 compares the results of computing a fault trace by the resolved-time method for values of v_h again equal to 8,000, 9,000, and 10,000 ft/sec, respectively, with those obtained by the curved-path method, which in this case produces a vertical fault trace. The velocity function of equation (14) was used

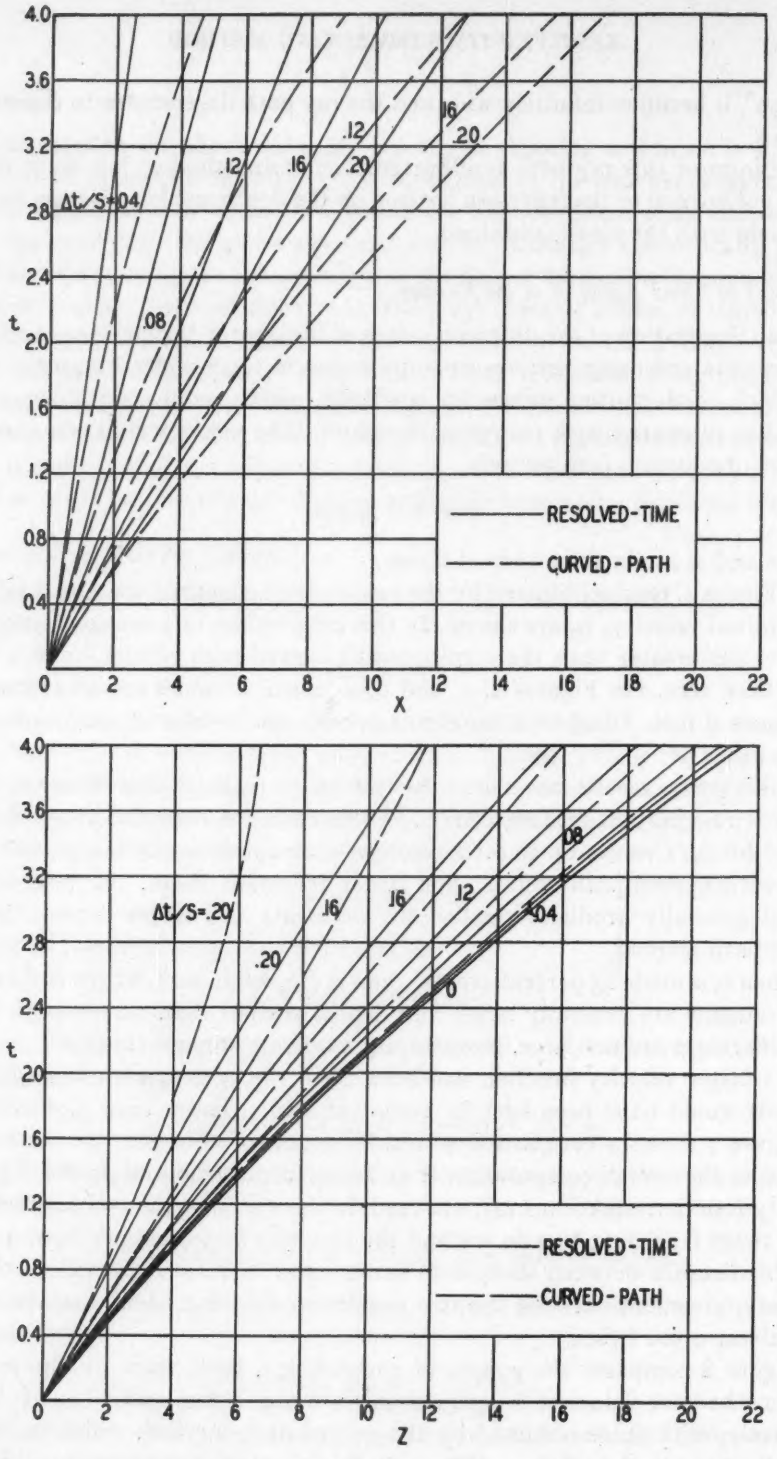

FIG. 4. Comparison of resolved-time method (using $v_A = 8{,}000$ ft/sec) with curved-path method for velocity function $v = 8 + 2.74\,\tau$; x represents horizontal displacement and z depth of the reflection point.

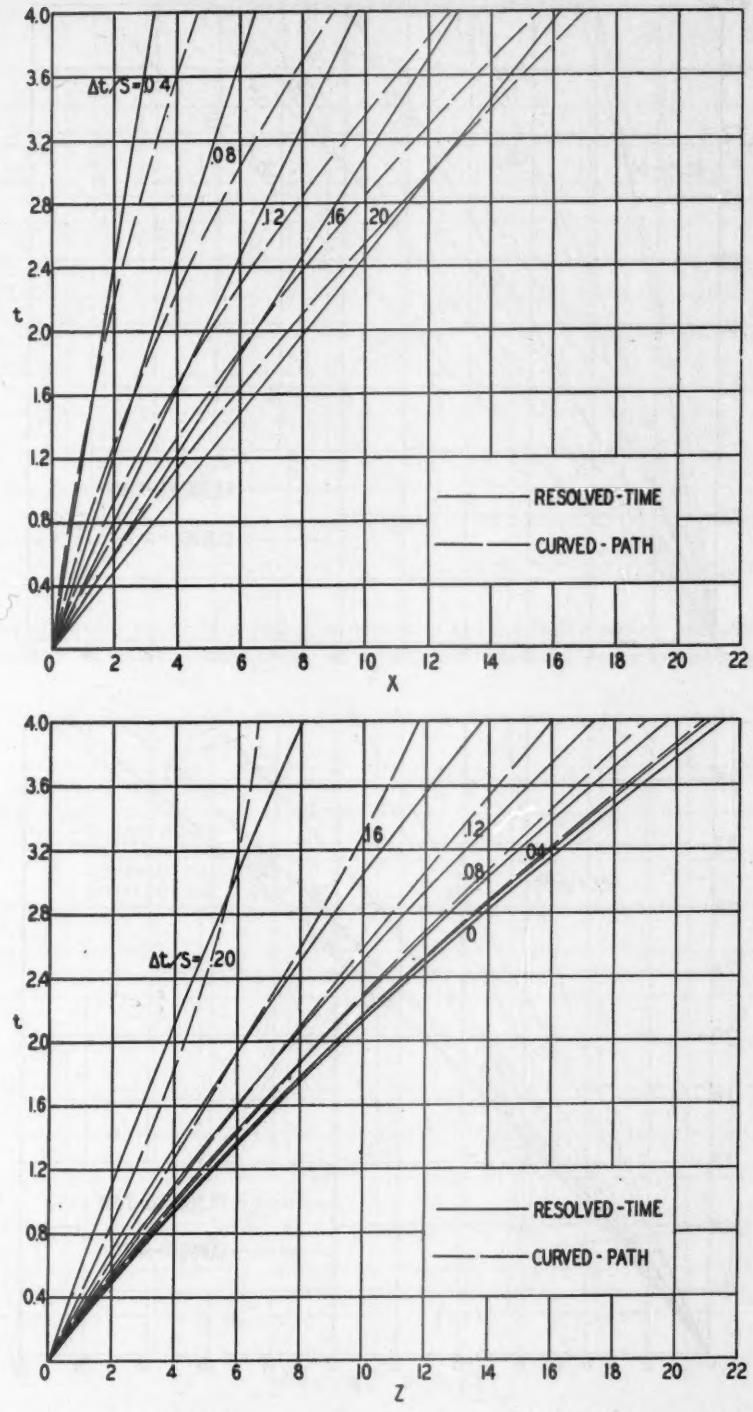

FIG. 5. Comparison of resolved-time method (using $v_h = 9{,}000$ ft/sec) with curved-path method for velocity function $v = 8 + 2.74\,\tau$; x represents horizontal displacement and z depth of the reflection point.

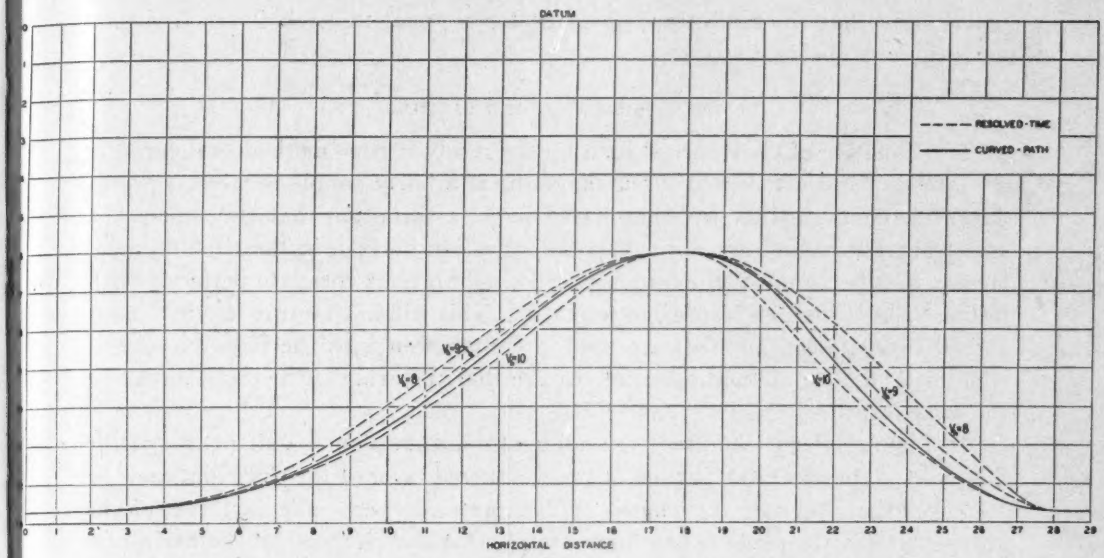

FIG. 7. Comparison of overall results of applying resolved-time method (using various horizontal velocities) and curved-path method to computation of asymmetric structural profile ($v=8+2.74\,\tau$).

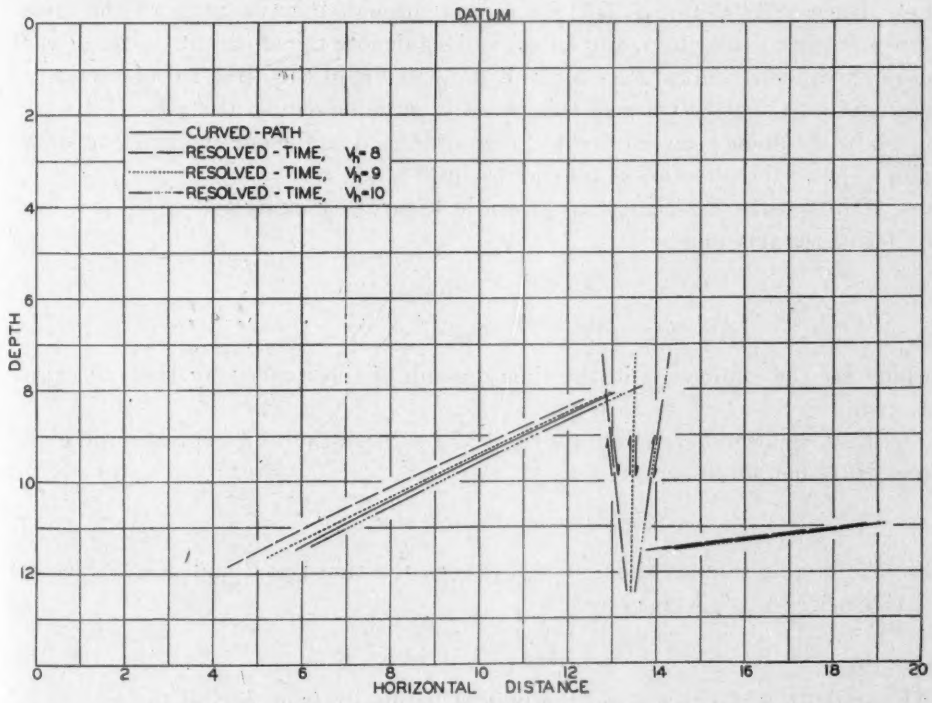

FIG. 8. Fault trace computed by resolved-time and curved-path methods ($v=8+2.74\,\tau$).

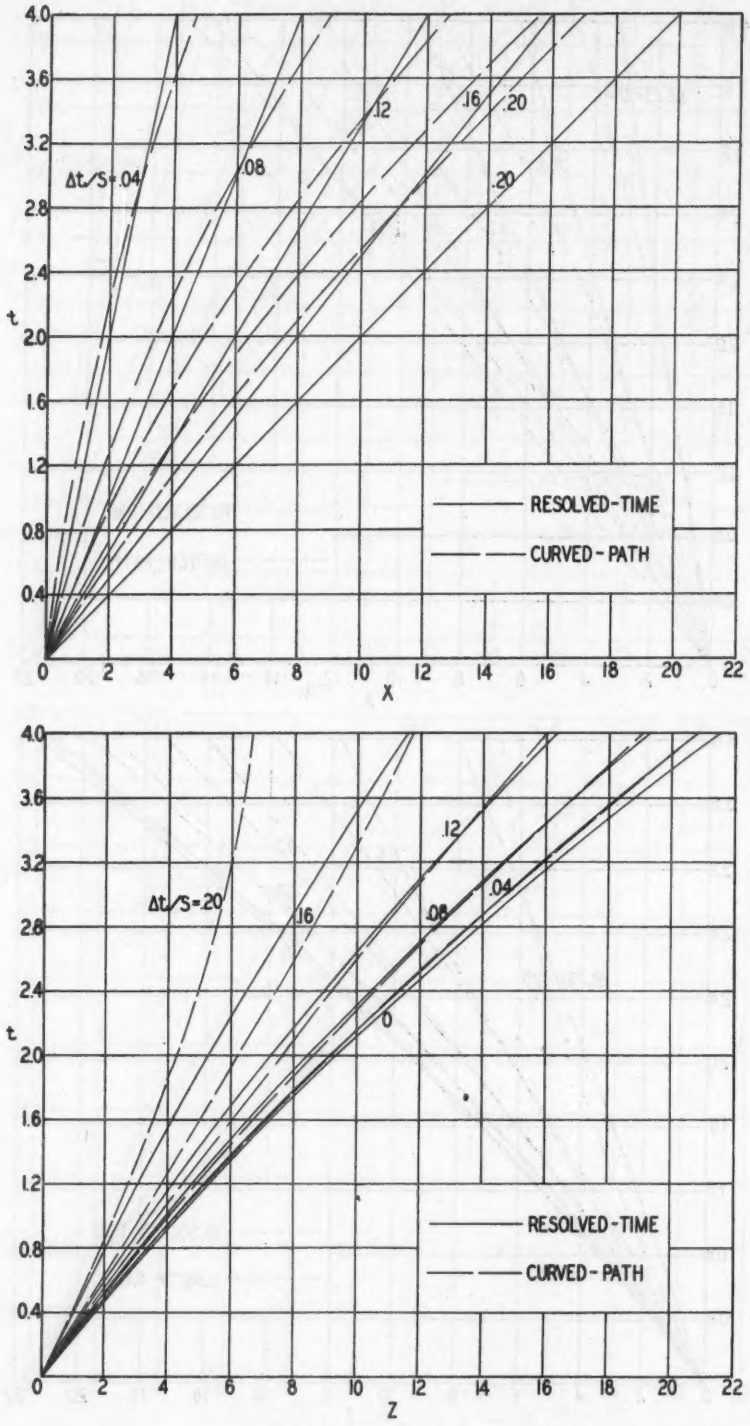

FIG. 6. Comparison of resolved-time method (using $v_h = 10{,}000$ ft/sec) with curved-path method for velocity function $v = 8 + 2.74\,\tau$; x represents horizontal displacement and z depth of the reflection point.

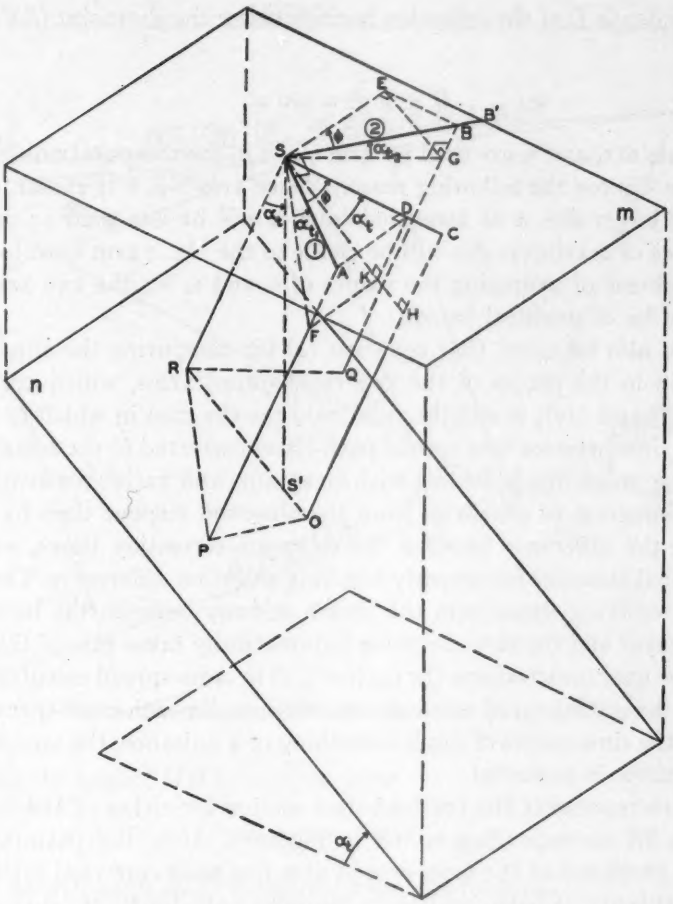

FIG. 9. Cross-spread computations.

$$t' = t - \Delta t', \tag{19}$$

where t represents the two-way time $2SR$ at the shotpoint.

The horizontal displacements and depths, in time units, of the points R and O corresponding to t and t' are found from equations (2) and (3) and are denoted by x_t, x_t', z_t, and z_t', respectively. The corresponding displacements, x and x', and depths, z and z', of the points R and O, respectively, are computed from relations (5) and (6), using the horizontal velocity appropriate for arm No. 1 as the value of v_h. Note that the quantities z_t and z_t' must be corrected to the datum below which the velocity function applies before being converted to depth values. This is done by adding the elevation-correction time at the shotpoint.

Finally, the true maximum angle of dip, α, is computed from equations (7), (8), and (9), where s is half the actual spread length of arm No. 1. One may also

again. Note that the fault trace obtained for v_h equal to 9,000 ft/sec is within one degree of being vertical.

CROSS-SPREAD COMPUTATIONS

The handling of cross-spread data by the resolved-time method to determine the direction and magnitude of maximum dip is a fairly simple numerical procedure. The computations are again based on the assumption that the time-paths are straight lines and are normal to the reflection horizon in the time domain. Hence, results obtained from cross-spread computations correlate perfectly with in-line values obtained from time resolution. This will not be true if other cross-spread computation methods are used in conjunction with the in-line resolved-time method. The method does not require that the arms of the cross-spread be the same length.

In Figure 9, let m represent the horizontal datum plane passing through the midpoint, S, between the bottom of the weathered layer at the shotpoint and the shot elevation. Let half the lengths of two mutually perpendicular arms of the cross-spread in the plane m be represented by SA and SB' and let the horizontal times, t_{h1} and t_{h2}, respectively, correspond to twice these lengths. Let n represent the plane of reflection in the time domain with an angle of dip of α_t, and let SR be the one-way time-path at the shotpoint which is assumed to be normal to n. Let planes ($SAPR$ and $SBQR$) be passed through the two arms of the cross-spread perpendicular to n, and let α_{t1} and α_{t2} denote the apparent time-angles of dip in these two planes. Pass a plane through SR in the direction of maximum dip, and let C on the trace of this plane in m be chosen so that $SC = SA = \frac{1}{2}t_{h1}$. Let ϕ be the angle between the No. 1 arm (defined as the one showing the larger dip, α_{t1}) and the direction of maximum dip.

With the other constructions shown in Figure 9 (making $SA = SB$), it is easy to derive the relations

$$\tan \phi = \sin \alpha_{t2} / \sin \alpha_{t1}, \tag{15}$$

$$\sin \alpha_t = \sin \alpha_{t1} / \cos \phi, \tag{16}$$

which are the equivalent in the time domain of those given by Heiland (1940, p. 526).

Using equation (15) to obtain $\cos \phi$ and substituting this expression in equation (16), one obtains

$$\sin \alpha_t = (\sin^2 \alpha_{t1} + \sin^2 \alpha_{t2})^{1/2}. \tag{17}$$

The double stepout time, $2CH$, between the times $2SR$ and $2CO$, which we shall denote by $\Delta t'$, is given by

$$\Delta t' = t_{h1} \sin \alpha_t. \tag{18}$$

The angle α_t is positive when the point C is up-dip from S, and the sign of $\Delta t'$ follows that of α_t. Then the two-way time, $t' = 2CO$, is computed from the relation

compute the depth D of the reflection horizon below the shotpoint (SS') from the relation

$$D = z + x \tan \alpha. \tag{20}$$

The values of t_h and v_h are used for arm No. 1 in the computations in the plane of maximum dip for the following reason: Since arm No. 1 is chosen as the one showing the larger dip, ϕ as measured from it will be less than 45 degrees and hence the line of maximum dip will be closer to the No. 1 arm than to the No. 2 arm. Any process of averaging the values of t_h and v_h for the two arms, if they differ, would be of doubtful benefit.

It should also be noted that equation (4) for computing the apparent time-angles of dip in the planes of the two cross-spread arms, which are needed in relations (15) and (17), is strictly valid only for the case in which Δt represents the stepout time between two normal path-times corrected to the same horizontal datum. Since, when one is dealing with steep dips and variable elevation corrections, it is incorrect to obtain Δt from the observed stepout time by adding or subtracting the difference between the elevation-correction times, we shall derive additional formulas for properly handling elevation differences. The graphical method of resolving times from the profile midway between the bottom of the weathered layer and the shot elevation automatically takes care of this difficulty and could be used to determine the α_{ti} ($i = 1, 2$) in cross-spread calculations. However, since the setting up of resolved-time sections for each cross-spread arm and measuring the time-angles of dip is something of a nuisance, the analytic method described below is preferred.

Figure 10 represents the resolved-time section for either of the cross-spread arms, with SR corresponding to SR in Figure 9. After the path-time $BR'FG$ to the end geophone of the cross-spread arm has been corrected for weathering and for angularity of path, we have a two-way path-time $2MA$ below the midpoint M which will be denoted by t_i ($i = 1, 2$). Then the stepout time Δt_i between the two-way path-time $t(= 2SR)$ at the shotpoint (assuming near-phone times have been averaged across the shotpoint) and t_i is given by

$$\Delta t_i = t - t_i, \tag{21}$$

and the angle SME, which we shall denote by α_{ti}', is found from

$$\sin \alpha_{ti} = \Delta t_i / t_{hi}. \tag{22}$$

It is assumed here and in equation (24) below that $SM = HM = \frac{1}{2} t_{hi}$, which is justified since the angle SMH is rarely over 5 degrees.

Now let t_e denote the two-way elevation-correction time at the shotpoint and t_{ei} the two-way elevation-correction at M. Then, setting

$$\Delta t_{ei} = t_e - t_{ei}, \tag{23}$$

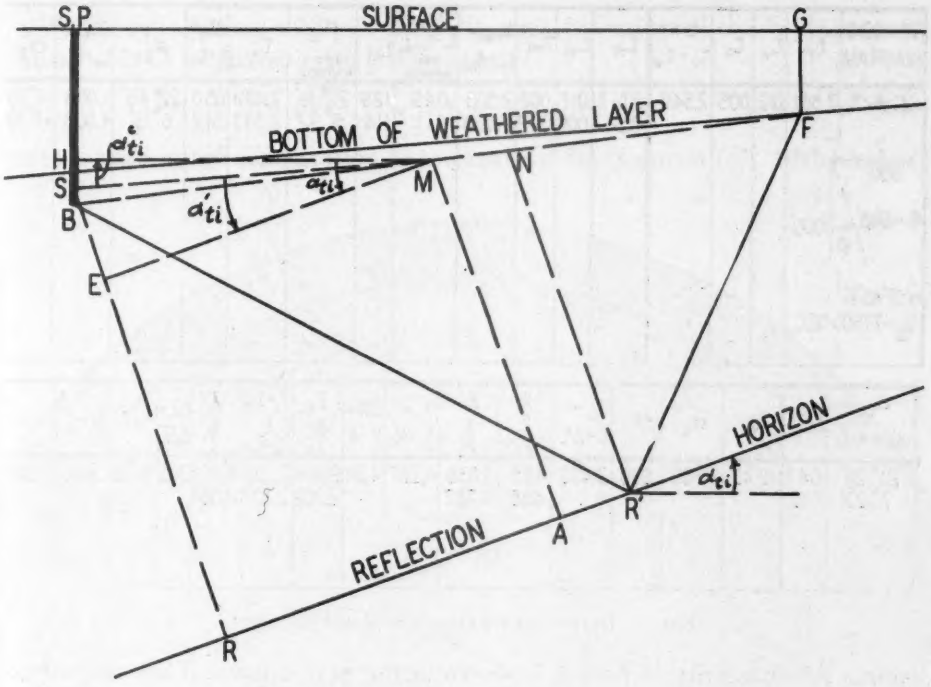

FIG. 10. Determination of α_{ti} in cross-spread computations.

and denoting the angle SMH by α_{ti}^{e}, we have

$$\sin \alpha_{ti}^{e} = \Delta t_{ei}/t_{hi}. \tag{24}$$

Hence, the desired angle α_{ti} is computed from the formula:

$$\alpha_{ti} = \alpha_{ti}' + \alpha_{ti}^{e}. \tag{25}$$

The signs of α_{ti}' and α_{ti}^{e} will follow those of Δt_i and Δt_{ei} respectively.

Figure 11 shows the data sheet used for the cross-spread computations, with an illustrative example worked out. The first column is devoted to the shotpoint number and cross-spread diagram, and the next four to the data at the shotpoint. The corresponding data for the end phones of the two arms of the cross-spread, with those for the No. 1 arm on the first line, are listed in the next four columns. The following column shows the first approximation to the stepout time Δt_i which is obtained by subtracting the time t_{rwi} over the angular path $BR'F$ (Figure 10) from t. This approximation is used along with the horizontal time shown in the next column to obtain a first approximation to α_{ti}' (formula (22)), which is listed in the following column. The purpose of this computation is to enable one to estimate the angle of dip, which must be considered in the correction for angularity of path if one is to obtain accurate results. The result of the cor-

S.P. NO. & DIAGRAM	t_r	t_w	t_e	$t = t_r - t_w$	t_{ri}	t_{wi}	t_{ei}	$t_{rwi} = t_{ri} - t_{wi}$	$\Delta t_i = t - t_{rwi}$ 1st APPROX.	t_{hi}	α'_{ti} 1st APPROX.	t_i	$\Delta t_i = t - t_i$	α'_{ti}	$\Delta t_{ei} = t_e - t_{ei}$	α^c_{ti}
120 W/S	2.561	.012	.005	2.549	2.517	.017	.008	2.500	.049	129	22° 19′	2.499	.050	22° 48′	-.003	-1° 20′
					2.547	.009	.002	2.538	.011	114	5° 32′	2.537	.012	6° 3′	+.003	+1° 30′

$\alpha_{ti} = \alpha'_{ti} + \alpha^c_{ti}$	$\Delta t'_i$	ϕ	α_t	$\Delta t'$	$t' = t - \Delta t'$	X_t & X'_t	X & X'	$Y = S + X'$	$\Delta X = Y - X$	Z_t & Z'_t	$Z_t + t_e$ & $Z'_t + t_e$	Z & Z'	$\Delta Z = Z - Z'$	α	D - Z	D
21° 28′	.047	19° 45′	22° 53′	.050	2.499	.495	3,836	4,267	431	2.348	2.353	14,469	382	41° 33′	3400	17,869
7° 33′	.015					.486	3,767			2.302	2.307	14,087				

FIG. 11. Data sheet for cross-spread computations.

rection for angularity of path t_i is shown in the next column. Then the correct values of Δt_i and α_{ti}' are computed and listed in the following two columns. In the example shown here, the final α_{ti}' values differ little from the first approximations since the corrections for angularity of path were small. In the worst cases, several approximations may be needed to obtain angularity of path corrections and α_{ti}' values with the desired accuracy. The next two columns are used to compute the correction angles α_{ti}^c and the final values of α_{ti} are listed in the following column. The $\Delta t_i'$ quantities in the next column are the stepout times after they have been corrected to the horizontal datum, plane m (Figure 9), by means of the relation

$$\Delta t_i' = t_{hi} \sin \alpha_{ti}, \tag{26}$$

which is analogous to equation (18). The last fifteen columns of the data sheet are devoted to the calculation of quantities in the plane of maximum dip which have already been explained.

Note that the computations can only be performed for the cases when both arms of the cross-spread are either on the up-dip or on the down-dip side of the shotpoint. Hence, in those cases in which one arm is on the up-dip side and the other on the down-dip side, the smaller dip of the two (No. 2 arm) is assumed to project without change through the shotpoint to the other side and the computation of ϕ, α_t, etc., is carried out on that basis. Of course, if one uses cross-spreads which are in the form of complete crosses (four arms), then it is generally possible to pair off the arms so that two will be on the up-dip side of the shotpoint and the other two on the down-dip side.

When one is dealing with two down-dip arms, the values of the displacements x and x' will be negative, as may the quantity

$$y = s + x', \tag{27}$$

which is used in the computation of the angle of dip (formula (9)). Although Δx

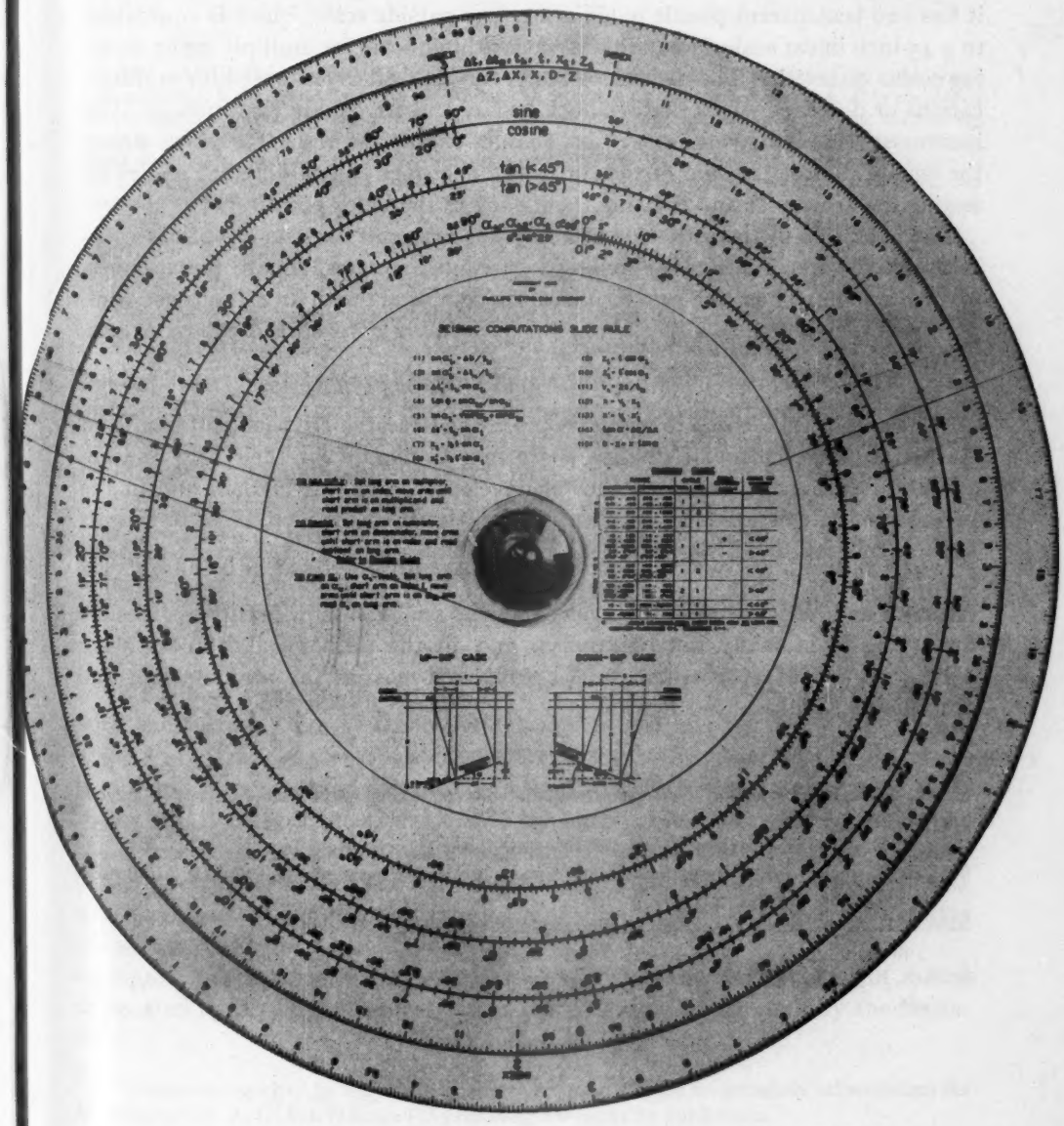

FIG. 12. Special slide rule designed for cross-spread computations.

GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 123–139, 10 FIGS.
(DISCUSSION ON PP. 140–147, 1 FIG.)

APPARENT RESISTIVITY FOR DIPPING BEDS*

KATSURO MAEDA†

ABSTRACT

The potential field of a point source of electric current, located on the surface of the earth above a dipping bed, is determined exactly by solving the appropriate differential equation. It is concluded that image theory is useful only in the two cases in which the reflection coefficient is plus one and the angle of dip is π/m and in which the reflection coefficient is minus one and the dip angle is $\pi/2m$, m being an integer. Computing methods are also developed for the cases in which the image theory is not applicable. Some numerical tables necessary for computation and several apparent resistivity curves are presented.

INTRODUCTION

Theoretical investigations concerning the potential field due to a point source of electric current, situated on the earth's surface above a dipping bed, have been published by Aldredge (1937) and Unz (1953). These investigations were based on the image theory, which is not always applicable. Unz pointed out this fact and developed a method by which apparent resistivity can be calculated approximately when the method of images is not valid.

The present work attempts to derive an exact solution for the potential and to demonstrate a method for computing the apparent resistivities. The dip angles are considered in relation to the ground surface which, for simplicity, is assumed to be horizontal. Isotropic and homogeneous layers are assumed in all calculations.

GENERAL SOLUTIONS

We choose a system of cylindrical coordinates (r, θ, z) whose z-axis coincides with the surface trace of the contact between two dipping beds (Fig. 1). The angle θ is taken counter-clockwise from the horizontal plane to the left of the z-axis, and r is the radial distance from that axis. The horizontal plane is given by $\theta=0$ to the left of the axis and by $\theta=\pi$ to the right. The interface separating the two media is given by $\theta=\alpha$. The resistivity of the upper layer is ρ_1 and that of the lower layer ρ_2. A fixed current electrode is located at the point $(r_0, 0, 0)$, which means that for this electrode $r=r_0$, $\theta=0$, and $z=0$. The current entering the ground through this electrode is I.

The distance between the current electrode and an arbitrary point (r, θ, z) is designated by R. The reciprocal of this distance can be expressed by the expansion,

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will always be positive, Δz will be negative in the down-dip case, and the negative quotient $\Delta z/\Delta x$ will give a negative angle of dip, as it should.

Although the cross-spread computations described above are simple, they are numerous and include trigonometric functions, squares, and square roots. Hence, a special 15-inch circular slide-rule was devised to facilitate the work. The front face of the slide-rule is shown in Figure 12. Like all standard circular rules, it has two transparent plastic index arms. The outside scale, which is equivalent to a 45-inch linear scale, is an ordinary logarithmic scale for multiplying or dividing scalar quantities. The next three scales are particularly adapted for multiplications or divisions which involve both scalars and trigonometric functions. The innermost scale is a special one which enables one to find the angle whose sine is the square root of the sum of the squares of the sines of two different angles by setting the arms once and rotating them back to the index point.

The back side of the slide-rule has only one arm and consists of ordinary logarithmic and linear scales for finding logarithms, squares, square roots, cubes, and cube roots. Thus, the rule provides the computers with an all-purpose computing device as well as a special one for performing cross-spread computations.

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(b) $$\frac{\partial V_2}{\partial \theta} = 0 \quad \text{when} \quad \theta = \pi.$$

(c) $$V_1 = V_2 \quad \text{and} \quad \frac{1}{\rho_1}\frac{\partial V_1}{\partial \theta} = \frac{1}{\rho_2}\frac{\partial V_2}{\partial \theta} \quad \text{when} \quad \theta = \alpha.$$

Using equation (1.3), the expressions for the potentials are assumed to be:

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{4}{\pi^2}\int_0^\infty \cos tzdt \times \int_0^\infty A(s)\left[\cosh s(\pi+\theta) + \cosh s(\pi-\theta)\right]K_{is}(tr_0)K_{is}(tr)ds\right\} \tag{1.4}$$

$$V_2 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{4}{\pi^2}\int_0^\infty \cos tzdt \int_0^\infty B(s)\cosh s(\pi-\theta)K_{is}(tr_0)K_{is}(tr)ds\right\}, \tag{1.5}$$

having been chosen in these particular forms in order to satisfy conditions (a) and (b). $A(s)$ and $B(s)$ are arbitrary functions which are to be chosen to satisfy the additional boundary conditions. In applying the boundary conditions (*c*), one must substitute the expansion (1.1) in equations (1.4) and (1.5). These conditions lead to the following pair of simultaneous equations:

$$A(s)\left[\cosh s(\pi+\alpha) + \cosh s(\pi-\alpha)\right] = B(s)\cosh s(\pi-\alpha) \tag{1.6}$$

$$(1+k)A(s)\left[\sinh s(\pi+\alpha) - \sinh s(\pi-\alpha)\right] + (1-k)B(s)\sinh s(\pi-\alpha) = 2k\sinh s(\pi-\alpha) \tag{1.7}$$

where k is the reflection coefficient equal to $(\rho_2-\rho_1)/(\rho_2+\rho_1)$. Solving these equations, we find that the unknown functions $A(s)$ and $B(s)$ are:

$$A(s) = \frac{k\sinh 2s(\pi-\alpha)}{2\cosh s\pi\left[\sinh s\pi + k\sinh s(2\alpha-\pi)\right]} \tag{1.8}$$

$$B(s) = \frac{k\left[\sinh s\pi - \sinh s(2\alpha-\pi)\right]}{\sinh s\pi + k\sinh s(2\alpha-\pi)}. \tag{1.9}$$

The potentials are now determined by substitution of the expressions for $A(s)$ and $B(s)$ in equations (1.4) and (1.5). With slight rearrangement,

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{4}{\pi^2}\int_0^\infty \cos tzdt \times \int_0^\infty \frac{k\sinh 2s(\pi-\alpha)\cosh s\theta}{\sinh \pi s + k\sinh s(2\alpha-\pi)}K_{is}(tr_0)K_{is}(tr)ds\right\} \tag{1.10}$$

$$V_2 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{4}{\pi^2}\int_0^\infty \cos tzdt\right.$$

$$\frac{1}{R} = \frac{4}{\pi^2}\int_0^\infty \cos tz dt \int_0^\infty \cosh s(\pi \pm \theta) K_{is}(tr_0) K_{is}(tr) ds \qquad (1.1)$$

where i is the square root of minus one and $K_{is}(tr)$ is a modified Bessel function of the second kind (Gray et al., 1922, p. 103). The upper sign in the quantity $(\pi \pm \theta)$ is chosen if $\theta < 0$ and the lower if $\theta > 0$. $K_{is}(u)$ is defined by the following relationships, where $J_n(u)$ is the ordinary Bessel function of the first kind:

$$I_n(u) = i^{-n} J_n(iu), \qquad K_n(u) = \frac{\pi}{2 \sin (n\pi)} [I_{-n}(u) - I_n(u)].$$

Laplace's equation in cylindrical coordinates is:

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2} + \frac{\partial^2 V}{\partial z^2} = 0. \qquad (1.2)$$

This partial differential equation is satisfied by the particular solution:

$$V = \cos tz \cosh s(\pi \pm \theta) K_{is}(tr). \qquad (1.3)$$

Let V_1 be the potential at a point in the upper material and V_2 that in the lower material. The boundary conditions which must be satisfied by V_1 and V_2 are:

(a) $$\frac{\partial V_1}{\partial \theta} = 0 \quad \text{when} \quad \theta = 0.$$

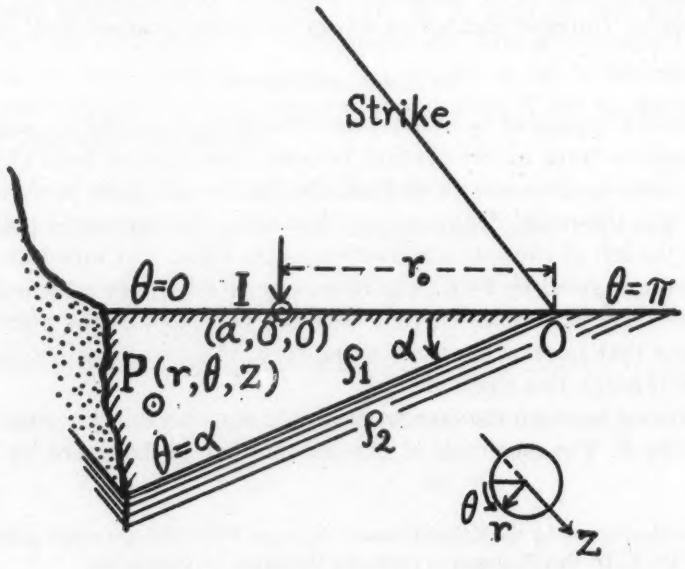

FIG. 1. Field of a point source situated on the earth above a dipping bed.

whence the potential can be expressed as

$$V = \frac{I\rho_1}{2\pi}\left\{\frac{1}{R} + \frac{4}{\pi^2}\int_0^\infty \cos tz\,dt \int_0^\infty \left[\cosh s\left(\pi + \theta - \frac{2\pi}{3}\right) + \cosh s\left(\pi + \theta - \frac{4\pi}{3}\right)\right] K_{is}(tr_0) K_{is}(tr)\,ds\right\}.$$

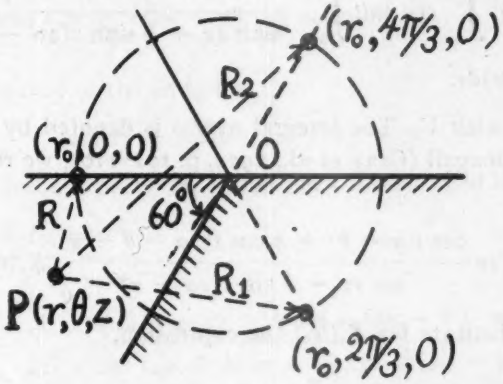

FIG. 2. Images of a point source situated at $(a, 0, 0)$. $(\alpha = 60°)$

The term $\cosh s[\pi+\theta-(2\pi/3)]$ leads to the expansion of $1/R_1$ and the term $\cosh s[\pi+\theta-(4\pi/3)]$ to the expansion of $1/R_2$, where R_1 and R_2 are as illustrated in Figure 2. Therefore, the potential function is:

$$V = \frac{I\rho_1}{2\pi}\left[\frac{1}{R} + \frac{1}{R_1} + \frac{1}{R_2}\right].$$

Thus, the potential function has been shown to be equal to the sum of potentials due to a point source at $(r_0, 0, 0)$, an image at $(r_0, 4\pi/3, 0)$, and a second image at $(r_0, 2\pi/3, 0)$.

But for $k = -1$, we have corresponding to (2.2)

$$-\frac{\cosh\frac{2\pi s}{3}\cosh s\theta}{\cosh\frac{\pi s}{3}} = \left[1 - 2\cosh^2\frac{\pi s}{3}\right]\frac{\cosh s\theta}{\cosh\frac{\pi s}{3}}.$$

This fraction is not reducible into a sum of cosine terms, so the potential V can not be expressed by a sum of reciprocal distances. In this case, potentials due to images cannot satisfy the boundary conditions.

TRANSFORMATION OF THE GENERAL SOLUTIONS

When the method of images is not useful, it appears that we must compute potentials using equations (1.10) and (1.11). But these integrals can be trans-

$$\times \int_0^\infty \frac{k[\sinh s\pi - \sinh s(2\alpha - \pi)]\cosh s(\pi - \theta)}{\sinh s\pi + k \sinh s(2\alpha - \pi)} K_{is}(lr_0)K_{is}(lr)ds \Big\} . \quad (1.11)$$

These expressions for V_1 and V_2 are general solutions to the problem.

METHOD OF IMAGES

We now consider two special cases. In the first, $k=1$ and the lower bed is a perfect insulator; in the second, $k=-1$ and the lower bed is a perfect conductor. In neither case do we need to consider the potential in the lower bed. Therefore, we replace V_1 simply by V. It can be shown that the fraction in the integrand of (1.10) reduces to:

$$k = 1: \quad \frac{\sinh s(\pi - \alpha)\cosh s\theta}{\sinh s\alpha} \quad (2.1)$$

$$k = -1: \quad -\frac{\cosh s(\pi - \alpha)\cosh s\theta}{\cosh s\alpha} . \quad (2.2)$$

We first consider the case for which $k=1$. Using the identities, $\sinh 2x = \sinh x(2\cosh x)$, $\sinh 3x = \sinh x(2\cosh 2x+1)$, etc., the denominator of (2.1) can be cancelled by a term in the numerator if $\pi-\alpha=m\alpha$ where m is an integer. In this case, $\alpha=\pi/(m+1)$ or, in other words, the angle of dip is a submultiple of π.

Next, in the case for which $k=-1$, we find useful the identities, $\cosh 3x = \cosh x(2\cosh 2x-1)$, $\cosh 5x = \cosh x(2\cosh 4x - 2\cosh 2x+1)$, etc. As in the previous case, the denominator of (2.2) can be reduced to unity only if $\pi-\alpha=\alpha(2m+1)$, in which case $\alpha=\pi/2(m+1)$. Here, the angle of dip must be a submultiple of $\pi/2$.

In both of these cases, the hyperbolic term in the integrand of (1.10) reduces to a sum of hyperbolic cosines. Further, if a source exists at the point $(r_0, \theta_0, 0)$ instead of $(r_0, 0, 0)$, the only change in (1.1) lies in replacing the factor $\cosh s(\pi \pm \theta)$ by $\cosh s(\pi \pm \theta \mp \theta_0)$. Thus, if the term containing hyperbolic functions in the integrand can be expressed by a sum of hyperbolic cosines, the potential function V can be expressed by a sum of the reciprocals of the distances between the observation point (r, θ_0, z) and images at the points $(r_0, \theta_0', 0)$. The result is the same expression for the potential which one would obtain by the method of images. In short, the method of images is useful in the two cases in which $k=1$ if the angle of dip is a submultiple of π and in which $k=-1$ if the angle of dip is a submultiple of $\pi/2$.

As an example, let us consider the problem in which $\alpha=\pi/3$. Corresponding to (2.1) when $k=1$, we have

$$\frac{\sinh \frac{2\pi s}{3}\cosh s\theta}{\sinh \frac{\pi s}{3}} = \cosh s\left(\pi + \theta - \frac{2\pi}{3}\right) + \cosh s\left(\pi + \theta - \frac{4\pi}{3}\right)$$

dues. In this instance, the only poles of the integrand lie on the real axis where the denominator of the integrand vanishes. Thus, we have transformed the integral into an infinite sum and

$$J_1 = \frac{\pi^2(1+k)}{2[\pi + k(2\alpha - \pi)]} K_0(tr)I_0(tr_0) + \pi^2 \sum_{m=1}^{\infty} \frac{\cos s_m(\pi - \theta) + k \cos s_m(2\alpha - \theta - \pi)}{\pi \cos s_m\pi + k(2\alpha - \pi)\cos s_m(2\alpha - \pi)} K_{s_m}(tr)I_{s_m}(tr_0), \qquad (3.4)$$

where s_m is a simple root of the equation,

$$\sin s\pi + k \sin s(2\alpha - \pi) = 0. \qquad (3.5)$$

It then follows that the potential V_1 has been transformed to:

$$V_1 = \frac{2I\rho_1}{\pi}\left\{\frac{K_0(tr)I_0(tr_0)^{1+k}}{2[\pi + k(2\alpha - \pi)} + \sum_{m=1}^{\infty} \frac{\cos s_m(\pi - \theta) + k \cos s_m(2\alpha - \theta - \pi)}{\pi \cos s_m\pi + k(2\alpha - \pi)\cos s_m(2\alpha - \pi)} \times \int_0^{\infty} K_{s_m}(tr)I_{s_m}(tr_0)\cos tz\,dt\right\}. \qquad (3.6)$$

We now designate by J_2 the integral over t in (3.6). Using the exponential form for the cosine, we may write:

$$J_2 = \frac{1}{2}\int_0^{\infty} [e^{itz} + e^{-itz}]K_{s_m}(tr)I_{s_m}(tr_0)dt.$$

In the transformation of this integral, we will make use of the following identities:

$$I_n(t) = e^{-(in\pi)/2}J_n(it), \qquad K_n(t) = e^{(in\pi)/2}G_n(it),^1$$

whence the integral can be rewritten as:

$$J_2 = \frac{-i}{2}\int_0^{i\infty} e^{-tz}G_{s_m}(tr)J_{s_m}(tr_0)dt - \frac{i}{2}\int_0^{i\infty} e^{tz}G_{s_m}(tr)J_{s_m}(tr_0)dt.$$

The first integral in this expression is transformed from an integral along the imaginary axis to one along the real axis by considering a contour integration consisting of both axes and an infinite quarter-circle in the first quadrant; there are no poles enclosed by this path. The second integral can be similarly transformed by using the corresponding path in the second quadrant. Therefore,

[1] These definitions are general, reducing to the previous ones given only when n is an integer.

formed to facilitate the computations. First, the expansion (1.1) is substituted for $1/R$ in (1.10) and (1.11). Then, after some arrangement, we get:

$$V_1 = \frac{2I\rho_1}{\pi^3}\int_0^\infty \cos tzdt \int_0^\infty \frac{\sinh s\pi[\cosh s(\pi-\theta) + k\cosh s(2\alpha-\theta-\pi)]}{\sinh s\pi + k\sinh s(2\alpha-\pi)} \times K_{is}(tr_0)K_{is}(tr)ds \tag{3.1}$$

$$V_2 = \frac{2I\rho_1}{\pi^3}(1+k)\int_0^\infty \cos tzdt \int_0^\infty \frac{\sinh s\pi \cosh s(\pi-\theta)}{\sinh s\pi + k\sinh s(2\alpha-\pi)} \times K_{is}(tr_0)K_{is}(tr)ds. \tag{3.2}$$

First, we deal with V_1. The integral over s is denoted by J_1. Following the method used by Dougall (Gray et al., 1922, p. 101–110), we rewrite the integral J_1 as:

$$J_1 = -i\int_0^{i\infty} \sin s\pi \frac{\cos s(\pi-\theta) + k\cos s(2\alpha-\theta-\pi)}{\sin s\pi + k\sin s(2\alpha-\pi)} K_s(tr_0)K_s(tr)ds. \tag{3.3}$$

If $r \geqq r_0$, we substitute for $K_s(tr_0)$ the expression,

$$K_s(tr_0) = \frac{\pi}{2\sin s\pi}[I_{-s}(tr_0) - I_s(tr_0)].$$

On the other hand, if $r \leqq r_0$, we may similarly substitute for $K_s(tr)$. Then, using the equality $K_{-s}(tr) = K_s(tr)$, we get:

$$J_1 = \frac{i\pi}{2}\int_{-i\infty}^{i\infty} \frac{\cos s(\pi-\theta) + k\cos s(2\alpha-\theta-\pi)}{\sin s\pi + k\sin s(2\alpha-\pi)} K_s(tr)I_s(tr_0)ds.$$

We now consider the contour integral,

$$i\frac{\pi}{2}\oint \frac{\cos s(\pi-\theta) + k\cos s(2\alpha-\theta-\pi)}{\sin s\pi + k\sin s(2\alpha-\pi)} K_s(tr_0)I_s(tr_0)ds,$$

where the integration is taken clockwise around a path consisting of the imaginary axis, indented to the right of the origin, and an infinite semi-circle to the right of the imaginary axis. The contribution from the large semi-circle is nil since the integrand vanishes exponentially as s becomes infinitely large. The integral around the indentation (an infinitesimal semi-circle) tends to:

$$-\frac{\pi^2(1+k)}{2[\pi + k(2\alpha-\pi)]} K_0(tr)I_0(tr_0).$$

And, finally, the remainder of the path along the imaginary axis is the integral J_1 whose evaluation we are seeking.

The value of the contour integral itself can be got from the theorem of resi-

$$J_2 = -\frac{i}{2}\int_0^\infty e^{-tz}[G_{s_m}(tr) - (-1)^n G_{s_m}(-tr)]J_{s_m}(tr_0)dt$$

$$= \frac{\pi}{2}\int_0^\infty e^{-tz}J_{s_m}(tr_0)J_{s_m}(tr)dt, \tag{3.7}$$

since

$$G_n(tr) - (-1)^n G_n(-tr) = \pi i J_n(tr).$$

This integral can be expressed by a Legendre function of the second kind (Watson, 1922, p. 389), so that:

$$J_2 = \frac{1}{2\sqrt{r_0 r}} Q_{s_m-1/2}\left[\frac{z^2 + r_0^2 + r^2}{2r_0 r}\right]. \tag{3.8}$$

Thus, the potential V_1 can be transformed for easy calculations. The second potential V_2 can be transformed in a like manner. Therefore, we can write instead of equations (1.10) and (1.11):

$$V_1 = \frac{I\rho_1}{\pi\sqrt{r_0 r}}\left\{\frac{1+k}{2[\pi + k(2\alpha - \pi)]} Q_{-1/2}(\xi) + \sum_{m=1}^{\infty} \frac{\cos s_m(\pi - \theta) + k\cos s_m(2\alpha - \theta - \pi)}{\pi \cos s_m\pi + k(2\alpha - \pi)\cos s_m(2\alpha - \pi)} Q_{s_m-1/2}(\xi)\right\} \tag{3.9}$$

$$V_2 = \frac{I\rho_1(1+k)}{\pi\sqrt{r_0 r}}\left\{\frac{Q_{-1/2}(\xi)}{2[\pi + k(2\alpha - \pi)]} + \sum_{m=1}^{\infty} \frac{\cos s_m(\pi - \theta)}{\pi \cos s_m\pi + k(2\alpha - \pi)\cos s_m(2\alpha - \pi)} Q_{s_m-1/2}(\xi)\right\}, \tag{3.10}$$

where $\xi = (z^2 + r^2 + r_0^2)/2r_0 r$ and s_m is a simple root of equation (3.5). The values of the Q's can be obtained from established tables or diagrams. They decrease so rapidly as m increases that the computations will not be troublesome.

SPECIAL CASES

Although $k = \pm 1$, the method of images is not always useful. But, if $k = \pm 1$, equation (3.9) becomes simple. Once again, we write V for V_1 since V_2 is unimportant. The roots of equation (3.5) are now easily seen to be $s_m = m\pi/\alpha$ if $k = 1$ and $s_m = (2m+1)\pi/2\alpha$ if $k = -1$. The potentials in these two cases then become:

$$\text{If } k = 1, \qquad V = \frac{I\rho_1}{\pi\alpha\sqrt{r_0 r}}\left\{(1/2)Q_{-1/2}(\xi) + \sum_{m=1}^{\infty} \cos\frac{m\pi\theta}{\alpha} Q_{(m\pi/\alpha)-1/2}(\xi)\right\} \tag{4.1}$$

$$\text{If } k = -1, \quad V = \frac{I\rho_1}{\pi\alpha\sqrt{r_0 r}} \sum_{m=1}^{\infty} \cos\frac{(2m+1)\pi\theta}{2\alpha} Q_{(2m+1)\pi/(2\alpha)-1/2}(\xi). \tag{4.2}$$

Note that the zero term has vanished in the second instance.

If the angle of dip has one of the special values which make the theory of images applicable, the potential may be calculated either from a consideration of the images or from equations (4.1) and (4.2). It follows that, in such cases, the right side of equation (4.1) or (4.2) can be expressed by the sum of reciprocal distances. This fact will be useful for numerical computations because, even when the method of images is not valid, part of the terms on the right side of (4.1) or (4.2) may be associated with images.

As an example, we consider the case in which $\alpha=\pi/3$. If $k=1$, the method of images is useful but, if $k=-1$, the image method is not valid. If $k=1$, from (4.1) and the method of images (Figure 2), we have:

$$V_1 = \frac{3I\rho_1}{\pi^2\sqrt{r_0 r}}\left\{\frac{1}{2}Q_{-1/2}(\xi) + \sum_{m=1}^{\infty}\cos 3m\theta Q_{3m-1/2}(\xi)\right\}$$

$$= \frac{I\rho_1}{2\pi}\left[\frac{1}{R}+\frac{1}{R_1}+\frac{1}{R_2}\right], \tag{4.3}$$

from which we see that the right side of (4.1) can be expressed by the sum of reciprocal distances. We will apply this relationship later. If $k=-1$, from (4.2), we have:

$$V = \frac{3I\rho_1}{\pi^2\sqrt{r_0 r}}\sum_{m=1}^{\infty}\cos\frac{3(2m+1)\theta}{2}Q_{3m+1}(\xi). \tag{4.4}$$

In this instance, the method of images is not applicable and we must base our computations on equation (4.4).

If $k\neq\pm 1$, we have from (3.9):

$$V_1 = \frac{I\rho_1}{\pi^2\sqrt{r_0 r}}\left\{\frac{1+k}{2[1-k/3]}Q_{-1/2}(\xi)\right.$$

$$\left.+\sum_{m=1}^{\infty}\frac{\cos s_m(\pi-\theta)+k\cos s_m(\theta+\pi/3)}{\cos s_m\pi - \frac{k}{3}\cos\frac{s_m\pi}{3}}Q_{s_m-1/2}(\xi)\right\} \tag{4.5}$$

where s_m is now a root of the equation, $\sin s\pi - k\sin(s\pi/3)=0$. This equation can be written as:

$$\sin\frac{s\pi}{3}\left[4\sin^2\frac{s\pi}{3}-3+k\right]=0. \tag{4.6}$$

From the first factor, we get the roots $s_m=3m$ $(m=0, 1, 2, \cdots)$ and, from the second factor, we get the roots $s_m=3(\beta+m)$ and $s_m=3(m+1-\beta)$ where $\beta=(1/\pi)$

arcsin $(\sqrt{3-k})/2$. The terms in V_1 associated with the first set of roots are

$$\frac{3I\rho_1(1+k)}{\pi^2\sqrt{r_0 r}(3-k)}\left\{\frac{1}{2}Q_{-1/2}(\xi)+\sum_{m=1}^{\infty}\cos 3m\theta Q_{3m-1/2}(\xi)\right\} \tag{4.7}$$

which can be calculated numerically by using (4.3) in which the relationship with images is shown. Accordingly, this term can be written as

$$\frac{I\rho_1(1+k)}{2\pi(3-k)}\left[\frac{1}{R}+\frac{1}{R_1}+\frac{1}{R_2}\right]. \tag{4.8}$$

Adding to equation (4.8) the terms due to the second set of roots, and letting $\theta=0$, we obtain the expression for the potential at the surface of the earth on the down-dip side of the surface trace of the contact between the two beds:

$$V_s=\frac{I\rho}{2\pi(3-k)}\left\{(1+k)\left[\frac{1}{R}+\frac{1}{R_1}+\frac{1}{R_2}\right]_{\theta=0}+\frac{6(1-k)}{\pi\sqrt{r_0 r}}\sum_{m=0}^{\infty}\left[Q_{3(m+\beta)-1/2}(\xi)+Q_{3(m-\beta)+5/2}(\xi)\right]\right\}. \tag{4.9}$$

Thus we see that for an arbitrary value of k, the potential V_1 can be expressed as the sum of a certain part which is due to images plus a second part which can not be associated with images. This fact is also true for other simple values of the angle of dip.

We now represent by $V_0=I\rho_1/2\pi R$ the potential at the surface of the earth if the earth were completely homogeneous. R is the distance between the fixed current electrode and the search electrode. Considerable convenience lies in the fact that the ratio V_s/V_0 is constant along each of a family of simple closed curves. Using equation (3.9), this ratio is found to be

$$V_s/V_0=\frac{2R}{\sqrt{r_0 r}}\left\{\frac{1+k}{2[\pi+k(2\alpha-\pi)]}Q_{-1/2}(\xi)+\sum_{m=1}^{\infty}\frac{\cos s_m\pi+k\cos s_m(2\alpha-\pi)}{\pi\cos s_m\pi+k(2\alpha-\pi)\cos s_m(2\alpha-\pi)}Q_{s_m-1/2}(\xi)\right\}. \tag{4.10}$$

We can see from (4.10) that the ratio is constant over a curve, on the surface of the earth, over which ξ and $R/\sqrt{r_0 r}$ are also both constant. From the geometry (Figure 3), we see that $R^2=(r-r_0)^2+z^2$. Therefore,

$$R/\sqrt{r_0 r}=\sqrt{\frac{1}{r_0 r}[(r-r_0)^2+z^2]}=\sqrt{\frac{1}{r_0 r}[z^2+r_0^2+r^2]-2}$$
$$=\sqrt{2(\xi-1)}. \tag{4.11}$$

That ξ is constant also implies that $R/\sqrt{r_0 r}$ is constant. In other words, V_s/V_0 must be constant along curves for which ξ is constant. Such curves are given by:

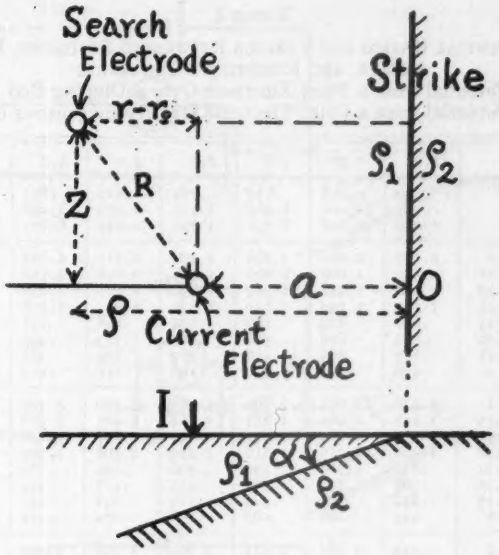

FIG. 3. Ground plan and cross section.

$$(z/r_0)^2 + (r/r_0)^2 + 1 = \text{constant} \times \frac{r}{r_0}. \qquad (4.12)$$

Clearly, the curves are a group of circles whose centers are on a perpendicular drawn from the current electrode to the surface trace of the contact between the beds. If we have the values of V_s/V_0 along a profile extending in any direction from the current electrode, we can easily get the values of the ratio along any other profile by using these auxiliary circles.

The ratios V_s/V_0, for various values of ξ, k, and α, have been tabulated in Table I. These data are of general utility and may be used to compute other quantities including apparent resistivities. The references in the table to "up-dip" and "down-dip" are to be used with respect to the fixed current electrode.

APPARENT RESISTIVITY

In Figure 4 are shown some typical electrode arrangements in a section perpendicular to the strike of the dipping beds. In each case, the current electrode nearest the surface trace is fixed and the electrode separation a is varied. The upper configuration is that used in the single-probe method; the second current electrode and a reference potential electrode are placed effectively at infinity. By composition of the results from more than one arrangement of this sort, we can compute the results for other electrode arrangements.

The middle arrangement represents the double equidistant probe method. Once again, the second current electrode is placed infinitely far away. The bottom diagram illustrates the Wenner configuration laid out perpendicular to the strike. The inter-electrode distances in the Wenner spread are all the same.

TABLE I

POTENTIAL RATIOS FOR VARIOUS RECORDING POSITIONS, DIP ANGLES, AND RESISTIVITY CONTRASTS

V_s = Potential from a Point Electrode Over a Dipping Bed

V_0 = Potential from a Point Electrode Over Homogeneous Earth

$\xi=(z^2+r^2+r_0)/2r_0r$			1.25	1.50	2.0	2.5	3.0	4.0	5.0	10.0	∞
R/r_0	Up-dip side		.500	.618	.732	.791	.821	.873	.899	.950	1.0
	Parallel to strike		.707	1.000	1.414	1.732	2.000	2.450	2.828	4.243	∞
	Down-dip side		1.000	1.618	2.732	3.791	4.821	6.873	8.899	18.950	∞
V_s/V_0	$\alpha=\pi/3$ 60°	$k=$ 1	1.756	2.000	2.265	2.414	2.512	2.633	2.706	2.852	3.000
		.75	1.526	1.688	1.862	1.969	2.032	2.112	2.156	2.240	2.333
		.50	1.330	1.438	1.545	1.590	1.630	1.677	1.705	1.755	1.800
		.25	1.141	1.190	1.241	1.270	1.294	1.316	1.321	1.344	1.364
		−.25	.880	.827	.780	.754	.748	.731	.719	.701	.692
		−.50	.761	.670	.588	.560	.525	.495	.473	.455	.429
		−.75	.653	.533	.416	.362	.323	.285	.259	.221	.200
		$k=-$ 1	.548	.410	.270	.196	.150	.102	.074	.026	0
	$\alpha=\pi/4$ 45°	$k=$ 1	2.228	2.655	2.992	3.204	3.330	3.507	3.605	3.802	4.000
		.75	1.792	2.061	2.255	2.384	2.461	2.578	2.613	2.689	2.800
		.50	1.472	1.615	1.727	1.792	1.837	1.896	1.915	1.967	2.000
		.25	1.220	1.276	1.318	1.344	1.368	1.393	1.396	1.410	1.428
		−.25	.837	.768	.730	.709	.699	.689	.678	.670	.667
		−.50	.686	.571	.513	.475	.457	.434	.420	.405	.400
		−.75	.554	.396	.323	.274	.248	.221	.207	.187	.182
		$k=-$ 1	.439	.289	.163	.106	.074	.042	.028	.007	0
	$\alpha=\pi/6$ 30°	$k=$ 1	3.244	3.861	4.475	4.801	5.008	5.259	5.408	5.703	6.000
		.75	2.305	2.621	2.917	3.070	3.175	3.281	3.332	3.440	3.500
		.50	1.720	1.936	2.017	2.087	2.189	2.192	2.199	2.236	2.250
		.25	1.311	1.373	1.422	1.444	1.468	1.486	1.489	1.496	1.500
		−.25	.772	.712	.675	.659	.656	.649	.644	.643	.643
		−.50	.573	.484	.422	.400	.391	.383	.377	.376	.375
		−.75	.411	.297	.221	.195	.184	.174	.169	.168	.167
		$k=-$ 1	.268	.139	.055	.028	.016	.007	.004	.000	0

For the single probe method, the apparent resistivity is defined as

$$\rho_a = 2\pi a \frac{V_s}{I}. \tag{5.1}$$

Therefore,

$$\rho_a/\rho_1 = V_s/V_0. \tag{5.2}$$

These values are the ones which can be read directly from the table.

Similarly, for the double equidistant-probe method:

$$\rho_a = 4\pi a \frac{V}{I} = \frac{4\pi a}{I}\left[V_s(a) - V_s(2a)\right] \tag{5.3}$$

and

$$\rho_a/\rho_1 = 2\frac{V_s(a)}{V_0(a)} - \frac{V_s(2a)}{V_0(2a)}. \tag{5.4}$$

V, as used in equation (5.3), is the potential difference between the two search electrodes.

For the Wenner configuration of electrodes, the apparent resistivity is given by

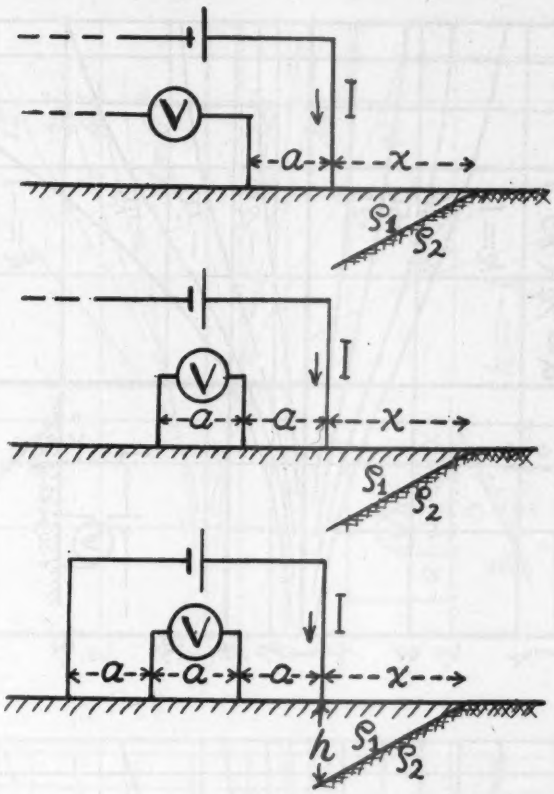

FIG. 4. Arrangement of electrodes. The upper is for two-electrode system, the middle for three-electrode system (double equidistant-probe method), and the bottom is for the Wenner set-up.

$$\rho_a = 2\pi a \frac{V}{I} \tag{5.5}$$

and the ratio ρ_a/ρ_1 can be calculated by properly combining the results from two configurations represented by equations (5.3) and (5.4)—one in which the search electrodes are down-dip from the current electrode and the other in which the search electrodes are up-dip.

Several apparent resistivity curves have been presented in Figures 5 through 10. In Figures 5, 6, and 7 are shown curves for the double equidistant-probe method for three values of the angle of dip. Curves for the Wenner configuration for various values of the angle α when the lower layer is a perfect insulator or a perfect conductor are shown in Figure 8. The line of electrodes is perpendicular to the strike of the dipping beds. Figures 9 and 10 show curves due to the Wenner configuration aligned parallel to the strike, for various values of k, when the angle of dip is 45 and 60 degrees, respectively.

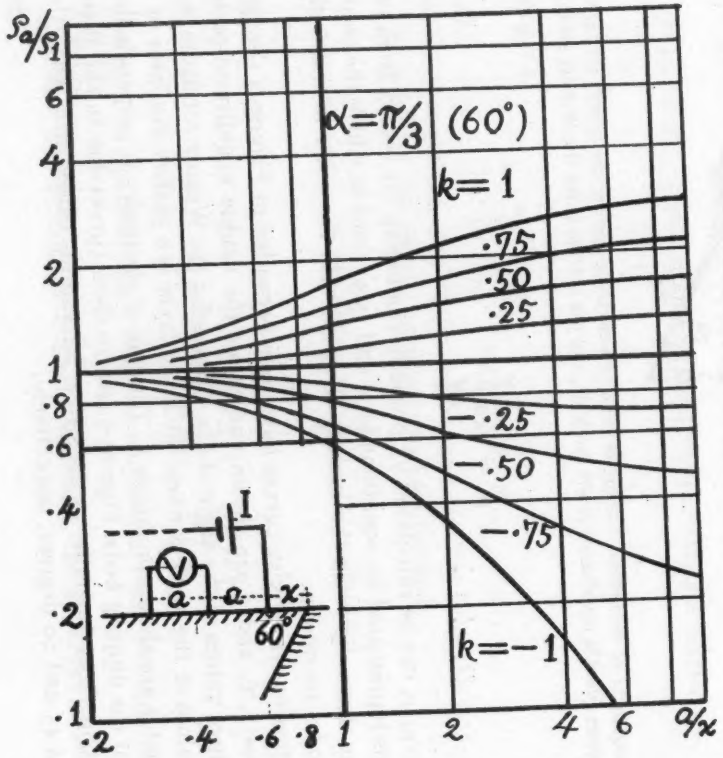

FIG. 5. Apparent resistivity curves for a dip angle of 60° at constant values of the reflection factor $-1 \leqq k \leqq 1$ as would be obtained by double equidistant-probe method, where search electrodes are laid out in the down-dip direction.

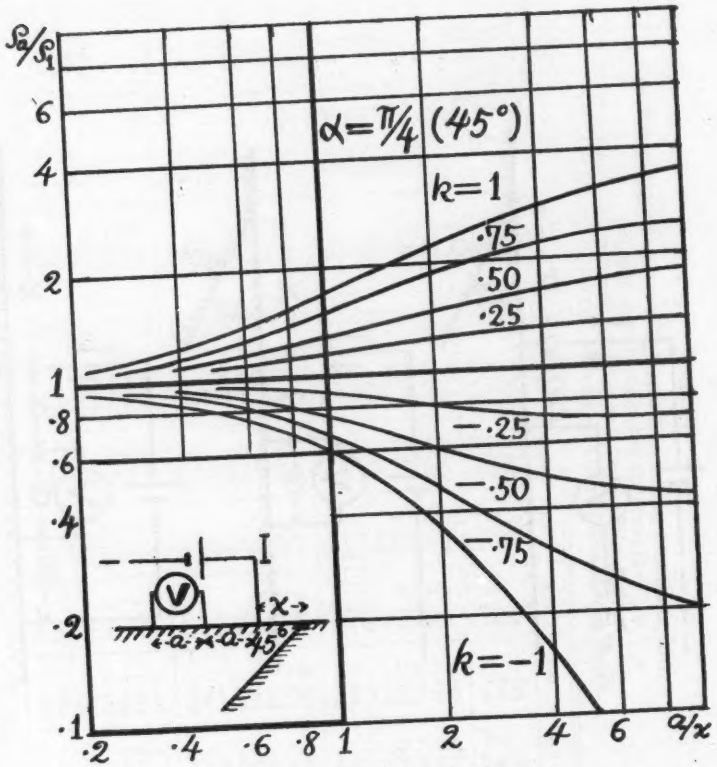

FIG. 6. Same as Figure 5 but for $\alpha = 45°$.

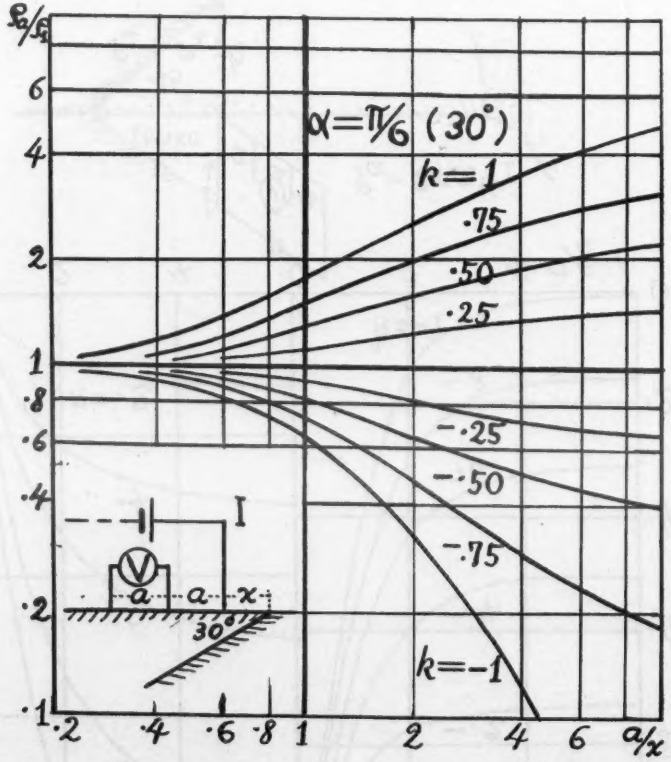

FIG. 7. Same as Figure 5 but for $\alpha = 30°$.

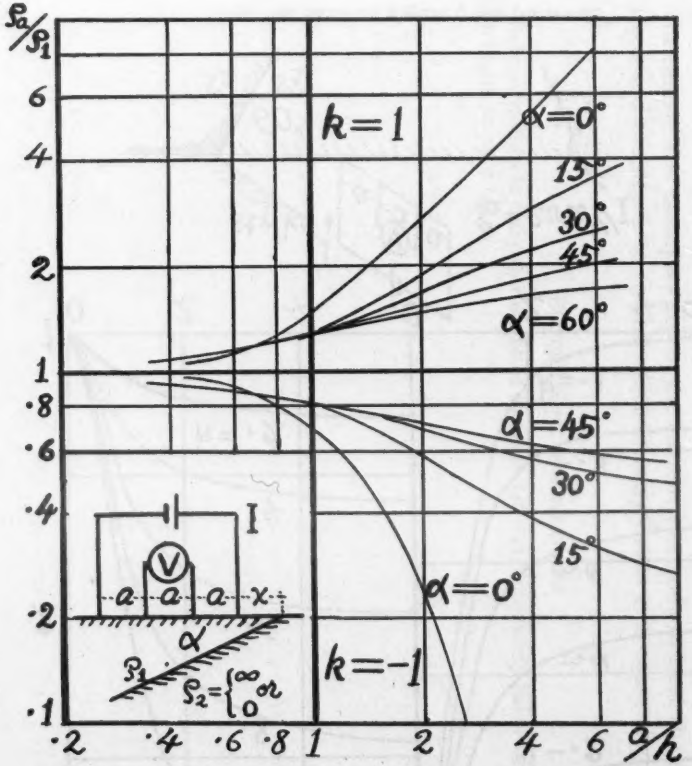

FIG. 8. Apparent resistivity curves for a dipping bed of high relative resistivity ($k=1$) and of high relative conductivity ($k=-1$) at constant dip angle α by the Wenner set-up, where electrodes are laid out in the direction of the down-dip side.

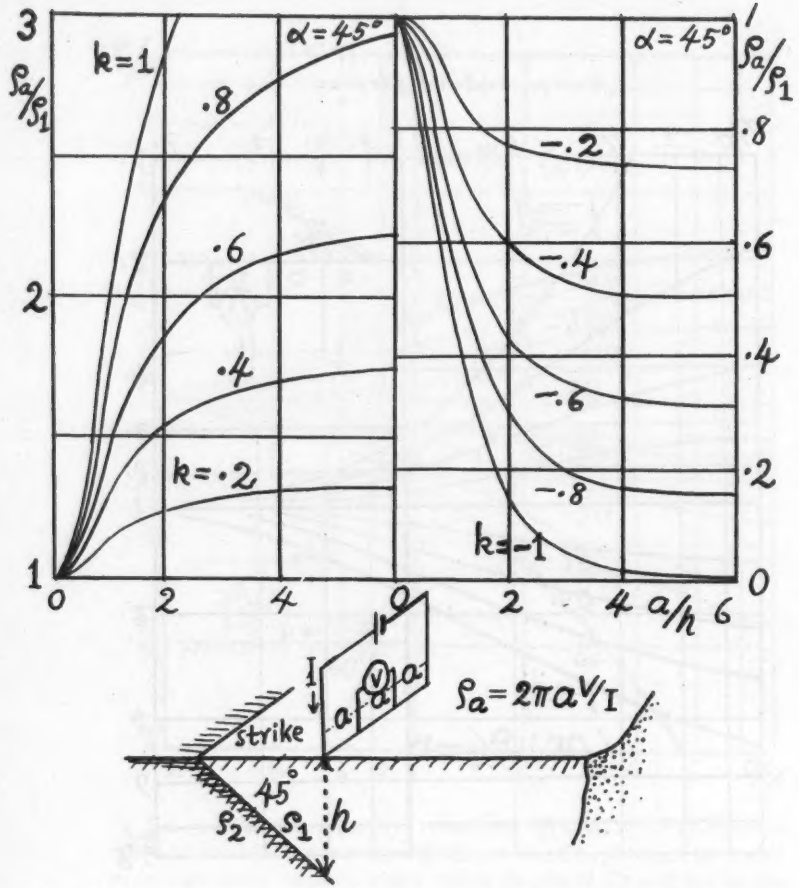

FIG. 9. Apparent resistivity curves for a dip angle $\alpha=45°$ at constant values of the reflection factor $-1 \leqq k \leqq 1$ by the Wenner set-up laid out parallel to strike.

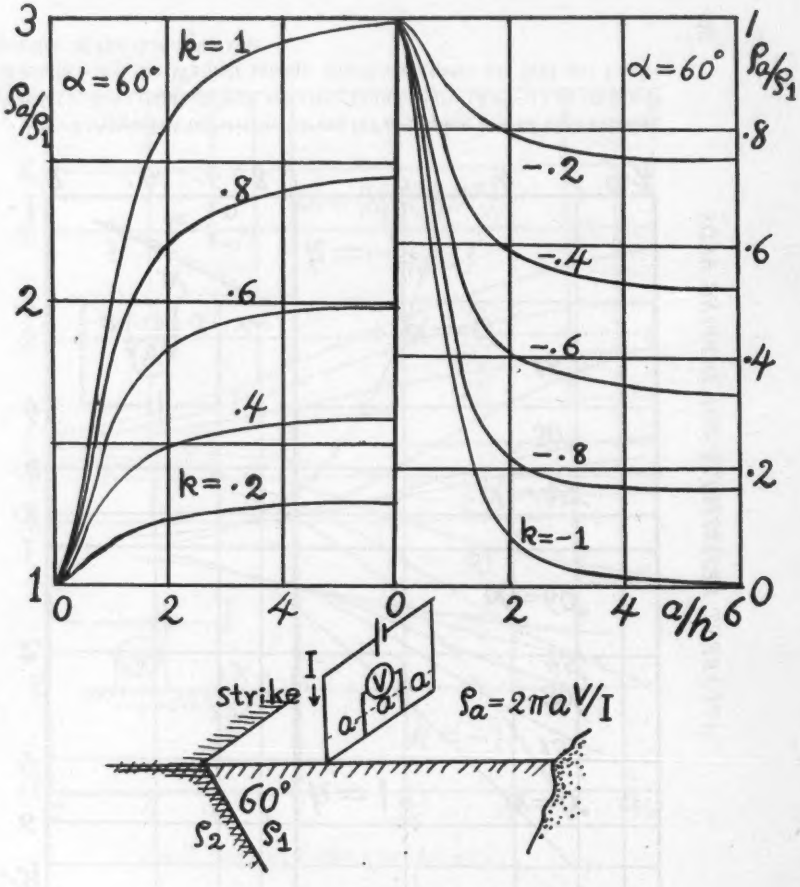

FIG. 10. Same as Figure 9 but for $\alpha=60°$.

In each of the examples given, the current electrode nearest the surface trace is fixed and the depth to the interface directly below this electrode is designated as h.

EDITOR'S NOTE ON REFERENCES

References cited in this paper are listed on pages 146–147 immediately following the discussion, which begins on page 140.

APPARENT RESISTIVITY FOR DIPPING BEDS—A DISCUSSION*

ROBERT G. VAN NOSTRAND† AND KENNETH L. COOK‡

Two groups of workers, here designated the "image school" and the "harmonic school" respectively, have attacked the problem of the interpretation of resistivity data over a dipping bed or dipping fault. The earlier attempts were made by the image school; but the more successful attempts have been made only recently by the harmonic school. The most successful work prior to that presented in the foregoing paper by Maeda has been done by the Russians, whose papers in their English translation are probably available to few American geophysicists. The purpose of this discussion is to appraise the relative merits of various prior solutions to the dipping bed problem in the light of the exact solution to the problem, which is given by Maeda. The terminology and symbols used herein are identical to those used by Maeda in his paper.

In the first general work to appear on electrical prospecting, Conrad Schlumberger (1920) showed how one can determine the direction of dip from an equipotential-line map. Weaver (1928) published a curve, assumed to be exact, which shows the departure from the normal of the potential due to two current electrodes placed over a bed with a ten per cent (slightly less than six degrees) dip where the resistivity of the overlying bed was ten times that of the lower bed. He compared this curve with the corresponding curve for a horizontal contact at a depth equal to the depth of the dipping contact at a point midway between the current electrodes. However, he did not tell how he arrived at the data from which the curve was drawn. Stern (1933) worked out a qualitative, graphical method for constructing resistivity curves over dipping beds. Since his results seem to represent an even less valuable approximation than those obtained through the use of the image theory, they will not be mentioned further in this paper.

THE IMAGE SCHOOL

The first use of images in the solution of the dipping bed problem was apparently made by Peters and Bardeen (1930). They derived the necessary governing equations for the potential distribution between two parallel, infinitely long, cylindrical-shaped electrodes (i.e., grounded wires) oriented along the surface in a direction parallel to the strike of the dipping beds. They treated only angles that are submultiples of $\pi/2$ and only cases in which the lower bed is either a perfect conductor or a perfect insulator. Because their electrodes were always placed in the upper formation, the method of images was always applicable for the *line* electrodes they assumed. The present discussion is primarily concerned with the interpretation of resistivity measurements made with *point* electrodes, which gives rise to the three-dimensional problem.

The first use of images in the solution of the dipping bed problem for point electrodes was made in a thesis written by Aldredge in 1933 and published by him in 1937 (Aldredge, 1937). He considers apparent resistivities as measured with the Wenner configuration oriented perpendicular to the strike of the dipping beds. Basically, his approach to the problem is an extension of the image solutions that had been successfully applied by others to *horizontal* beds. It is shown below that an extension of the image theory, such as that used by Aldredge, to the dipping bed problem is valid only in a few special cases. Moreover, in adapting the image theory—as it had been previously used for horizontal

* This discussion of the preceding paper by Maeda has been invited by the Editor. Received October 8, 1954.

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beds—to the dipping bed problem, Aldredge modifies the theory by restricting the number of images to $\pi/2\alpha$, or to the next smaller integer if $\pi/2\alpha$ is not an integer. Although he does not state his reasons, Aldredge apparently bases this restriction on an analogy, which we consider basically unsound, between electric fields and the reflection of light by mirrors. For a given electrode separation and resistivity contrast, Aldredge's restriction introduces a discontinuity in the potential function as the angle of dip α is increased through a submultiple of $\pi/2$, because at such a value of α the function is affected by one less image than it is at an infinitesimally smaller angle. Because his assumptions are not valid generally, and because the necessary boundary conditions are not satisfied, Aldredge's solutions are at best only approximations.

Aldredge's theoretical work, without modification, became the basis for four other papers (Sanjeevareddi, 1936; Jameson, 1941; Carreno, 1948; and Trudu, 1952), all of which obviously contain the same shortcomings in theory as did Aldredge's original paper. Sanjeevareddi extended the resistivity studies and added several apparent resistivity curves to the set presented by Aldredge in 1933. Also he tried to check the earlier theoretical work by some ingenious model studies. However, because of experimental difficulties, which he acknowledged, we believe his model results were inconclusive with regard to the validity of the theoretical work. Jameson applied Aldredge's potential functions to potential-drop-ratio studies over dipping beds. Carreno similarly applied Aldredge's potential functions to a modification of the potential-drop-ratio method as it is used in the United States. Trudu (1952) extended the principle which Aldredge had set down by computing resistivity curves for a variety of configurations and orientations of the line of electrodes.

Roman (1951), in a general review of resistivity methods, condemns the use of the "light" analogy for the dipping bed problem, but retains the principle that the use of the image theory has general application, even for the dipping bed problem.

Early workers in potential theory recognized the restrictions on the image theory when applied to the wedge problem in electrostatics (MacDonald, 1895); but Unz (1953) was the first in the geophysical literature to acknowledge the limited validity of the image theory. Unz shows by logical analysis that image theory is valid only when the dip angle is a submultiple of π if the bottom layer is perfectly insulating, or a submultiple of $\pi/2$ if the bottom layer is perfectly conducting. He points out that image theory is not strictly applicable for intermediate resistivity contrasts but that "the deviations caused by this distortion are negligible at small absolute values of the reflection factor k and also at sharp dip angles. . . . " He then proceeds to set up potential functions for angles which are submultiples of π and for general values of the reflection factor. He assumes that the correct positions of the images are the positions that they would occupy were the lower bed perfectly insulating ($k=1$), that there would be only one image at each point, and that there would be no other images. He concludes that the greatest error, in applying this assumption to the Wenner configuration laid out parallel to the strike, is found in the asymptotic value of the apparent resistivity as the electrode separation is made very large. It is possible to compute these asymptotic values directly from elementary considerations and thus he has some check on the degree of error in his approximations.

Unz further tries to infer the accuracy of his assumption by determining the error involved when only a limited number of images is used to calculate apparent resistivities for a given two-layer problem for various values of the electrode separation. Since this check is concerned only with order of magnitude and seems to be satisfactory in that respect, he concludes that his approximation is "fieldworthy."

Although there are many curves presented in the other papers discussed above, the only strictly exact curves are presented by Unz for the apparent resistivity as measured with the Wenner configuration in the upper formation and oriented parallel to the strike of the dipping beds. In each of Unz's curves, the constant parameter is the distance from the line of electrodes to the contact plane along a line perpendicular both to the line of electrodes and to the plane. His graphs show 1) apparent resistivity versus electrode separation for $k=+1$ and various angles of dip, 2) apparent resistivity versus electrode separation for $k=-1$ and various angles of dip, 3) apparent resistivity versus angle of dip

for $k=+1$ and various electrode separations, and 4) the asymptotic value of the resistivity versus angle of dip for various positive values of k. Of the other curves in the literature, all are approximate to some degree; Unz's approximate curves, as compared to the other approximate curves, stand on the firmest ground since he has tried to analyze the degree of approximation. None of the above authors, including Unz, claims to have derived a potential function which is valid on the up-dip side of the surface trace of the contact between the dipping beds. Indeed, there has been no treatment by members of the image theory school which would enable one to cross the contact with his electrode configuration.

To conclude our discussion of the image school, attention is directed to the work of Keller (1953), who determines very formally all of the shapes of perfect conductors for which a Green's function may be formed by the use of image theory. Basically, the reason why images are not valid in the general case is that, in order to satisfy conditions at the boundaries through the use of images, singularities must be introduced in regions where there should be none. The facts which we have discussed above are consistent with Keller's findings.

THE HARMONIC SCHOOL

The harmonic school had an early start in the field of potential theory, and has given ever-increasing help in the solution of many geophysical problems. It is only recently, however, that the full power of harmonic analysis has been utilized in solving completely the dipping bed problem.

An electrostatic problem involving point charges can be readily converted to a corresponding current problem involving point sources of current merely by properly changing the constants in the solution and by properly choosing a plane to represent the earth's surface. Thus the solutions of the wedge problem in electrostatics can be converted to valid solutions of the dipping bed problem in direct current theory. If the electrostatic solution is in cgs units, the corresponding electrodynamic solution is obtained by substituting $I\rho/4\pi$ for q/κ, where κ is the dielectric constant. Similarly if the electrostatic solution is in mks units, $I\rho$ is substituted for q/ϵ, where ϵ is the capacitivity.

MacDonald (1895) obtained solutions for the potential due to a point charge in the vicinity of the intersection of two conducting planes. He investigated the many ramifications of his solution and showed that it was equivalent to a solution due to a set of images only if the wedge angle (which is twice our angle of dip) is a submultiple of π. He also showed that when the wedge angle is an odd submultiple of 2π, the solution reduces to a closed form with a finite number of terms. In terms of the set-up and symbols used by Maeda, MacDonald's solution becomes:

$$\left.\begin{aligned} V_1 &= \frac{I\rho_1}{\alpha}\sum_{n=0}^{\infty}\sin^2\frac{n\pi}{2}\cos\frac{n\pi\theta}{2\alpha}\int_0^{\infty} e^{-s|z|}J_{n\pi/2\alpha}(sr_0)J_{n\pi/2\alpha}(sr)\,ds \\ V_2 &= 0 \end{aligned}\right\} \tag{1}$$

Rice (1940) simply wrote down a solution to the general problem of the field due to a point charge in the vicinity of a dielectric wedge and then proceeded to verify that the solution satisfied all of the conditions of the problem. He manipulates his initial solution, which contains integrals involving the Legendre function of the second kind

$$Q_{i\rho-1/2}\left(\frac{r^2+r_0^2+z^2}{2r_0r}\right),$$

into summations of the form of Maeda's equations 3.9 and 3.10.

Russian workers were apparently the first group of theoretical geophysicists to attack rigorously the general problem of electrical prospecting with point electrodes over dipping beds. Markov (1938) derived a complex solution using Neumann's ring coordinates, but his solution is limited to the case in which the underlying bed is perfectly conducting. Tikhonov (1946) obtained a solution to the appropriate integral equations by means of successive approximations. Tiurkisher (1946) extended these solutions and showed that part of the solution reduced to a complete elliptic integral. Some approximate curves, based on Tikhonov's method, for dip angles of 30° and 45° were published

by Berel'kovskiy and Zubanov (1951). The theoretical work of this group culminated in the studies of Skalskaya (1948), who obtained a complete solution to the problem for all possible angles of dip, following a modification of the procedure established by Grunberg (1940) in solving the corresponding electrostatic problem. Although her procedure, which involves the use of a Fourier-Bessel type integral transformation, is slightly more complicated than Maeda's direct solution of the differential equation, Skalskaya's general solution is identical to Maeda's equations 1.10 and 1.11. Also, she has shown that the general solutions reduce to the correct expressions in the limiting case at large distances from the current electrode. She further demonstrates that her results reduce to MacDonald's equation when ρ_2 approaches zero. Skalskaya has also reduced the general solutions to comparatively simple expressions for the potential distribution on the surface of the earth when the dip angle has certain values. For example, when $\alpha=\pi/4$:

$$V_1=\frac{I\rho_1}{2\pi}\left\{\frac{1}{R}+\frac{2k}{\sqrt{r^2+r_0^2+z^2}}+\frac{k^2}{\sqrt{(r+r_0)^2+z^2}}-\frac{k(1-k^2)}{\sin\delta}\int_0^\infty\frac{\sinh\delta sds}{\sinh\pi s\sqrt{(r+r_0)^2+z^2+4rr_0\sinh^2\frac{\pi s}{4}}}\right\} \tag{2}$$

$$V_2=\frac{I\rho_1}{2\pi}\left\{\frac{1+k}{R}+\frac{k(1+k)}{\sin\delta}\int_0^\infty\frac{\sinh\delta sds}{\sinh\pi s\sqrt{(r+r_0)^2+z^2+4rr_0\sinh^2\frac{\pi s}{4}}}\right\}. \tag{3}[1]$$

And for $\alpha=3\pi/4$:

$$V_1=\frac{I\rho_1}{2\pi}\left\{\frac{1}{R}+\frac{k}{\sin\delta}\int_0^\infty\frac{\sinh(\pi-\delta)sds}{\sinh\pi s\sqrt{(r+r_0)^2+z^2+4rr_0\sinh^2\frac{\pi s}{4}}}\right\} \tag{4}$$

$$V_2=\frac{I\rho_1}{2\pi}\left\{\frac{1+k}{R}-\frac{k(1+k)}{\sin\delta}\int_0^\infty\frac{\sinh(\pi-\delta)sds}{\sinh\pi s\sqrt{(r+r_0)^2+z^2+4rr_0\sinh^2\frac{\pi s}{4}}}\right\} \tag{5}$$

where $\cos\delta=-k/2$. Comparatively simple expressions may also be derived for other angles which are submultiples of π or their supplements. We feel that expressions of this type are the most suitable yet presented for computation of resistivity data over dipping beds.

A paper by Šumi (1953) has been brought to our attention too late for us to check its contents. According to *Geophysical Abstracts*, "Šumi derives formulas for computing the dip from apparent resistivities obtained, valid for any value of the dip." We do not know whether the work of Šumi falls into one of our two classifications or into a third empirical group.

Turning now to Maeda's paper itself, we find it on the whole to be an excellent, direct treatment of the problem. We would contest, however, the fact that computations, based on equations 3.9 and 3.10, are always simple. The function $Q_\nu(\xi)$ becomes infinite as ξ approaches unity. This fact becomes especially important when these equations are being used to compute horizontal resistivity profiles perpendicular to the strike. In this case, $z=0$. Then, when the current and potential electrodes straddle the surface trace of the contact between the dipping beds, and r becomes nearly equal to r_0, the function

$$Q_{s_m-1/2}\left(\frac{r^2+r_0^2+z^2}{2rr_0}\right)$$

becomes very large. Although the potential function as a whole tends to some finite value as r approaches r_0 (Rice, 1940), computations based on these equations become unwieldy. Moreover, we

[1] This expression is derived in Skalskaya's paper. She merely wrote down the other three without derivation.

know of no satisfactory tabulation of the Legendre functions of the second kind of arbitrary order such as are required in this sort of computation.

COMPARISON OF APPARENT RESISTIVITY CURVES

Finally, we present a diagram showing curves (Figure 1 of Discussion) based on the approximations which have been previously offered, together with the correct vertical profile curves for beds dipping at an angle of 45°. The resistivity contrast is 1 to 4, the upper set of curves representing the case in which the upper bed is most conducting and the lower set the case in which the lower bed is most conducting. The Wenner configuration is aligned parallel to the strike of the beds, as shown in Maeda's Figure 9. The apparent resistivity is plotted against the electrode separation on logarithmic paper as it most likely would be in the field. The exact curves are based on equation (2) above. The integral was evaluated by Simpson's Rule, dividing the intervals $0 \leqq s \leqq 1$ and $1 \leqq s \leqq 4$ each into six parts. The remainder for $s > 4$ is negligible, being less than 0.05%. Computations for the approximate curves are based on equations given by the respective authors.

For $k = +0.6$, we see that Unz was correct in assuming that the maximum error in his raw curve was in its asymptotic value. His modified curve very closely approximates the true curve, displaying an error of only 3.5% at about $a = 2$. It is interesting to note that the Aldredge curve, which is based on an unacceptable premise, is about as good as the Unz corrected curve in this case. Unz's modified curves for $k = -0.6$ contains a maximum error of about 15% at $a = 2$. In this case, Aldredge's approach leads to a negative apparent resistivity, which is possible in some cases of very complex geology but is impossible here.

We emphasize that this example, both with respect to the resistivity contrast and to the angle of dip if that angle is a submultiple of π, embodies about the maximum error possible in Unz's approximation.[2] Therefore, it should be borne in mind that errors in approximations for other angles or for other resistivity contrasts would at worst be only slightly larger than those shown in this example and would probably be less. Of course, there would be no error when $k = \pm 1$, when $\alpha = 0°$, or when $\alpha = 90°$.

CONCLUSIONS

General conclusions, especially those concerning the accuracy of approximations applied to examples other than the one chosen, must await a more thorough study that includes variations of all the parameters, such as angle of dip, resistivity contrast, and orientation of the electrode configuration. Without exact numerical computations, the quantitative influence of the parameters upon the character of the apparent resistivity curves is often unpredictable. We are currently making such comparative studies and the results will be made available later.

We emphasize that Unz's analysis is restricted to traverses lying in the upper bed and oriented parallel to the strike of the dipping beds. His approximations seem to be adequate for positive reflection factors but are borderline for negative reflection factors.

For positive reflection factors, the apparent resistivity curves based on Aldredge's method warrant checking to ascertain the limits of their reliability in the case of profiles taken both parallel and perpendicular to the strike of the dipping beds.

Maeda's paper is the first in English to give a complete solution to the dipping bed problem for all values of the angle of dip and for all resistivity contrasts. Of the various expressions available for computations, however, we prefer ones of the type presented by Skalskaya and given herein; they are not subject to convergence restrictions and do not require tables of special functions.

REPLY BY DR. MAEDA TO PRECEDING DISCUSSION

It was a pleasure for me to receive a copy of the discussion of my paper by Drs. Van Nostrand and Cook. Through their detailed description, the previous studies on dipping beds and the relation between them have been greatly clarified.

[2] This idea was suggested by Unz upon reading a preliminary draft of this discussion.

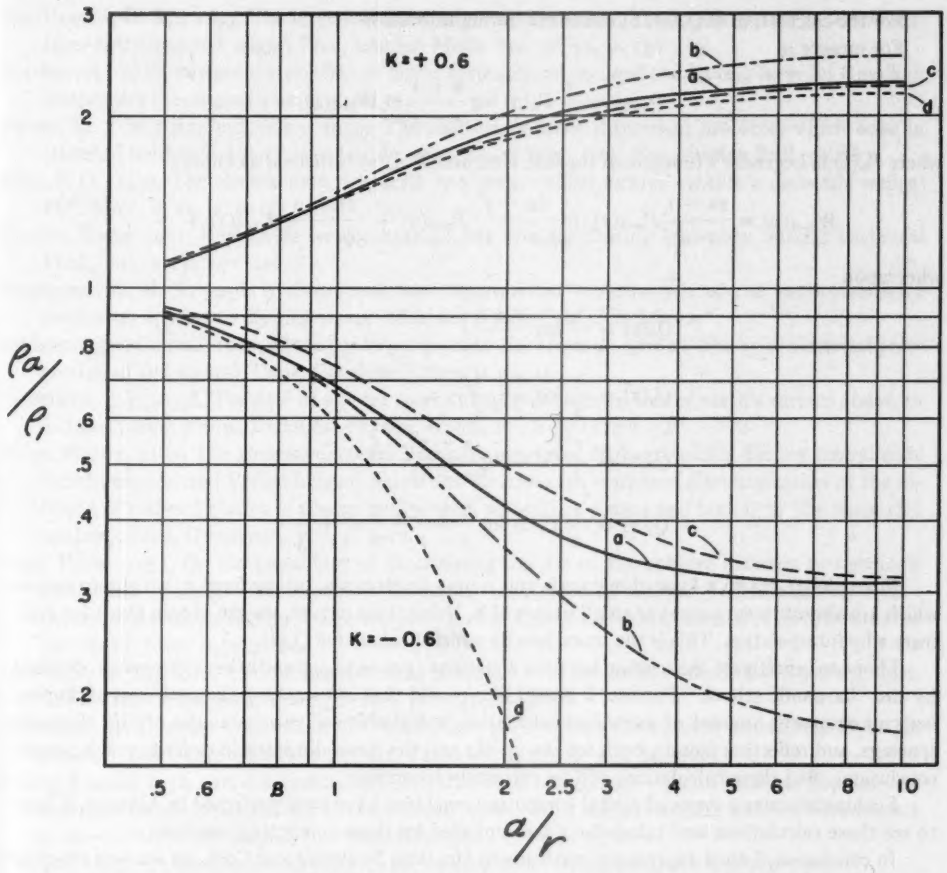

FIG. 1 OF DISCUSSION. Comparison of approximate resistivity vertical profiles (Wenner configuration) with exact curves for $k = \pm 0.6$, $\alpha = 45°$, and with line of electrodes parallel to strike. a) Exact curves based on Maeda and Skalskaya. b) Unz preliminary curves based solely on images. c) Unz corrected curves. d) Aldredge curves. See also Maeda's Figure 9.

They point out that in the case $z=0$, the function Q becomes very large as r becomes nearly equal to r_0, making numerical calculation complex. This difficulty, I think, is inevitable. Legendre's function of the 2nd kind $Q_\nu(x)$ is defined for $|x|>1$, as follows:

$$Q_\nu(x) = \frac{2^\nu(\nu!)^2}{(2\nu+1)!}\,\frac{1}{x^{\nu+1}}\left\{1 + \frac{(\nu+1)(\nu+2)}{2(2\nu+3)}\,\frac{1}{x^2} + \frac{(\nu+1)(\nu+2)(\nu+3)(\nu+4)}{2\cdot 4(2\nu+3)(2\nu+5)}\,\frac{1}{x^4} + \cdots\right\},$$

The case where $z=0$ and $r=r_0$ corresponds to $x=(r^2+r_0^2+z^2)/2rr_0=1$. We must avoid the case where $x=1$, since the calculation becomes necessarily unwieldy as r approached to r_0.

According to Dougall (Gray et al., 1922) there ought to be three possible forms of Green's function generally containing Bessel functions, each of which has its own region of rapid convergence. My expression (3.9) or (3.10) is one of these forms and I believe that it should be possible to obtain other forms. Then the calculation about $x=1$ might become easy. For the present, the above-mentioned difficulty can not be removed. Since, however, the limit of apparent resistivity is ρ_1 as r approaches to r_0 and $z=0$, we can use the method of interpolation.

For the calculation of $Q_\nu(x)$, I used the following expression:
For integer n,

$$Q_n(x) = \frac{1}{2} P_n(x) \log \frac{x+1}{x-1} - W_{n-1}(x),$$

where $P_n(x)$ is Legendre's function of the first kind and $W_{n-1}(x)$ is defined as follows:

$$W_{n-1}(x) = \frac{2n-1}{1 \cdot n} P_{n-1}(x) + \frac{2n-5}{3(n-1)} P_{n-3}(x) + \frac{2n-9}{5(n-2)} P_{n-5}(x) + \cdots,$$

whereupon

$$Q_0(x) = \frac{1}{2} \log \frac{x+1}{x-1},$$

$$Q_1(x) = \frac{x}{2} \log \frac{x+1}{x-1} - 1,$$

$$Q_2(x) = \frac{1}{2} P_2(x) \log \frac{x+1}{x-1} - \frac{3}{2} x,$$

$$Q_3(x) = \frac{1}{2} P_3(x) \log \frac{x+1}{x-1} - \frac{5}{2} x^2 + \frac{2}{3}.$$

If we plot $Q_n(x)$ on a logarithmic scale and n on a linear scale, taking fixed x, we obtain curves which are almost linear except at small values of n. Using these curves, we can obtain $Q_\nu(x)$ for arbitrary ν by interpolation. This is the procedure by which I calculated $Q_\nu(x)$.

I hope to investigate the relation between equations (3.9) or (3.10) and other expressions obtained by the "harmonic school." Further, I should like to add that in attacking the problems of dipping beds an enormous amount of numerical calculation is desirable for various angles of dip, electrode spacings, and reflection factors, both for the up-dip and the down-dip sides, in order to reach general conclusions. But these calculations will be extremely laborious.

Fortunately many types of digital computing machines have been perfected in America. I hope to see these calculations and tabulations accomplished by these computing machines.

In conclusion, I must express my gratitude to Drs. Van Nostrand and Cook for sending me their discussion and for bringing many other references to my attention.

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ELEMENTARY DERIVATION OF A FORMULA

An alternate to Peters' (1949) derivation is the following one:

Let $U(P)$ be the potential at the point P due to a surface distribution of density, $\sigma(Q)$, on a level plane below P. Then

$$U(P) = \int \frac{\sigma(Q)dA(Q)}{r_{QP}}, \tag{1}$$

where $dA(Q)$ is an element of area associated with the point Q, r_{QP} is the distance from P to Q, and the integration is over the whole infinite plane.

Taking the positive z axis vertically downward, we find by direct differentiation

$$\frac{\partial U(P)}{\partial z} = \int \frac{\cos \psi(P, Q)\sigma(Q)dA(Q)}{r_{QP}^2}, \tag{2}$$

where ψ is the angle between the vector from P to Q and the positive z direction. As $\cos \psi\ (P, Q)dA(Q)/r_{QP}^2$ is the element of solid angle, viewed from P, subtended by the element of area, $dA(Q)$, it is not difficult to show that if $\sigma(Q)$ is bounded and continuous, then as P approaches a point Q_1 on the surface of mass distribution, in the limit

$$\partial U(Q_1)/\partial z = 2\pi\sigma(Q_1), \tag{3}$$

and so equation (1) may be rewritten

$$U(P) = \frac{1}{2\pi}\int \frac{\partial U(Q)/\partial z}{r_{QP}}\, dA(Q). \tag{4}$$

Equation (4) expresses the solution of the Neumann problem for the plane case for any function U satisfying Laplace's equation. But both $g(P)$ and $\partial g(P)/\partial z$ satisfy Laplace's equation in this case and therefore equation (4) may be rewritten:

$$\frac{\partial g(P)}{\partial z} = \frac{1}{2\pi}\int \frac{\partial^2 g(Q)/\partial z^2}{r_{QP}}\, dA(Q). \tag{5}$$

To complete the derivation, note that if any constant is added to the $U(P)$ in equation (4) or to $\partial g(P)/\partial z$ in equation (5) the Neumann problem will still be solved by the sum. We fix the constant by supposing $U(P)$ and $\partial g(P)/\partial z$ approach zero as $z \to -\infty$. Thus for our purposes (4) and (5) are correct and complete as they stand.

Let us use cylindrical coordinates. Then (5) becomes

$$\frac{\partial g(0, z, 0)}{\partial z} = \int_0^\infty \frac{(\partial^2 g(r, 0)/\partial z^2)rdr}{(r^2 + z^2)^{1/2}}, \tag{6}$$

GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 148–154, 2 FIGS.

THE FIRST VERTICAL DERIVATIVE OF GRAVITY*

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ABSTRACT

A formula is given which permits the relatively convenient calculation of the first vertical derivative of gravity in terms of the distribution of the second vertical derivative of gravity. The use of the formula is illustrated in a simple case. The formula is compared to Evjen's with respect to convenience of use.

INTRODUCTION

Evjen (1936, p. 134, equations (16) and (19)) has given a formula for the computation of the first vertical derivative of gravity. It is based upon the solution of the problem of Dirichlet in potential theory (Kellogg, 1929, p. 236; Hadamard, 1930, p. 49–56, 74; Gunther, 1934, p. 152–193). This problem is usually stated for a closed region: the earth, for example. At the surface, the gravitational potential may be supposed everywhere known. The (exterior) Dirichlet problem is then that of finding the potential due to the mass distribution of the earth at all exterior points from the values of the potential given on the surface. The Dirichlet problem used by Evjen is an extension to the limiting case of the infinite half space (Hadamard, 1930, p. 74). In this case, if $U(x, y, z)$ is the potential, then gravity, $g(x, y, z) = \kappa \partial U/\partial z$, where κ is the Newtonian gravitational constant, satisfies Laplace's equation and the Dirichlet problem solution formula (Evjen, 1936, p. 133, equation (13)) can be applied directly in this case.

Another boundary value problem of potential theory may be applied to the problem, namely the Neumann problem. Here the normal derivative of the potential (normal to the boundary surface) is given and the harmonic function (satisfying Laplace's equation) is to be found from this given data. Now the first derivative, $\partial g/\partial z$, satisfies Laplace's equation (for the case of the infinite plane boundary) and so if we know $\partial^2 g/\partial z^2$, which is easily found (Evjen, 1936, p. 128, equation (4)), then we can calculate $\partial g/\partial z$ by the formula for the solution of the Neumann problem. We use this latter mode of approach.

Nothing really new is claimed in theory. Our formula is given by Peters (1949, p. 305, equation (32)). We only claim that our expression may be more convenient than Evjen's in some cases. It has been more convenient in several practical cases. The integral that has to be evaluated graphically appears to be more rapidly convergent and easier to handle.

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We have made contour maps for g and $\partial^2 g/\partial z^2$ taking care to use practically the same number of contours in each case. Our rough block graphs are shown in Figures 1 and 2, using our expression and Evjen's respectively. Our very rough result using Figure 1 and equation (8) is $\partial g/\partial z = 0.155 \times 10^{-6}$ gals/meter. Using Figure 2 and equation (10) we get $\partial g/\partial z = 0.55 \times 10^{-6}$ gals/meter.

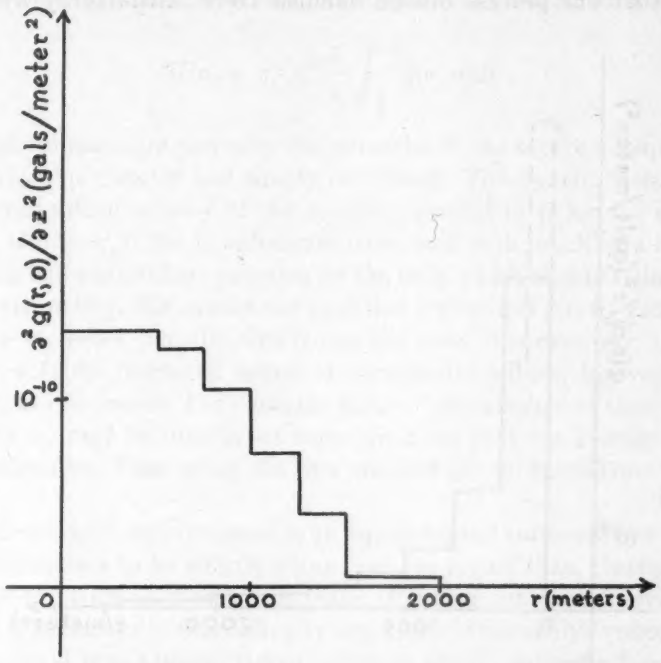

FIG. 1. Graph of $\partial^2 g(r, 0)/\partial z^2$ vs. r for approximate determination of $\partial g(0, 0, 0)/\partial z$ by the method of the present paper.

An investigation discloses that there are two major sources of error in the latter result. One is due to the approximate treatment of the graphical integration near $r = 250$ meters. Rather than plot $g(r, 0)/r^2$ it is better to plot $g(r, 0)$ and use the mean value theorem (Franklin, 1940, p. 201, equation (49)). This brings the value down to 0.345×10^{-6} gals/meter.

Another cause of error is cutting off equation (10) at $r = 2{,}500$ instead of at ∞. Taking account of this originally neglected part of the integral we come down to 0.145×10^{-6} gals/meter.

COMPARISON OF METHODS

If a second vertical derivative map of an area is available, as it usually is if the calculation of the first vertical derivative is contemplated, we think our formula a little easier to apply than Evjen's. Azimuthal averaging and graphical integrations are required in any case. Our formula is convergent without special

where

$$\frac{\partial^2 g(r, o)}{\partial z^2} = \frac{1}{2\pi}\int_0^{2\pi} \frac{\partial^2 g(r, o, \theta)}{\partial z^2}\, d\theta. \tag{7}$$

For $z=o$, equation (6) becomes

$$\frac{\partial g(o, o, o)}{\partial z} = \int_0^{\infty} \frac{\partial^2 g(r, o)}{\partial z^2}\, dr. \tag{8}$$

Equation (8) and (7) constitute our basic formulae. Evjen's corresponding formulae are

$$g(r, o) = \frac{1}{2\pi}\int_0^{2\pi} g(r, o, \theta) d\theta \tag{9}$$

and

$$\frac{\partial g(o, o, o)}{\partial z} = \frac{g(R, o)}{R} - \int_R^{\infty} \frac{g(r, o)}{r^2}\, dr, \tag{10}$$

where R is the radius of the circle bounding the area within which $g(r, o)$ may be considered constant.

Jeffreys (1938, p. 310–311) has given a discussion similar to Evjen's and finds

$$\frac{\partial g(o, o, o)}{\partial z} = \frac{2g(o, o, o) - g(R, o)}{R} - \int_R^{\infty} \frac{g(r, o)}{r^2}\, dr. \tag{11}$$

In the example given, the correction of Jeffreys' expression amounts to about 2%, which is quite negligible. Jeffreys (1938, p. 310) indicates that Green (1828, p. 58) gave a closely related formula.

APPLICATION

Consider a horizontal plane at a depth of 1,000 meters. To the left of a reference line let the surface density on this plane be zero and to the right let it be 2,000 g/cm². This corresponds approximately to a slab with a density difference of +0.2 g/cm³ and a thickness of 100 meters at an average depth of 1,000 meters. At the datum level we have

$$g = 2\kappa\sigma(\pi - \tan^{-1}(z/x)), \tag{12}$$

$$\partial g/\partial z = -2\kappa\sigma x/(x^2 + z^2) \tag{13}$$

and

$$\partial^2 g/\partial z^2 = 4\kappa\sigma xz/(x^2 + z^2)^2 \tag{14}$$

where z is the depth and $+x$ is the distance to the right (over the mass). Take $x=+1{,}000$ meters. Then $g=6.28\times10^{-4}$ gals and $\partial g/\partial z=1.33\times10^{-7}$ gals/meter.

treatment of the origin neighborhood. It is easier to surround a second derivative map with an outer region where the second derivative is identically zero (and thus secure rapid convergence at $r = \infty$) than it is to handle the corresponding problem for Evjen's integral. Regional effects have already almost disappeared from our second derivative map.

We feel that our process can be handled more satisfactorily by personnel

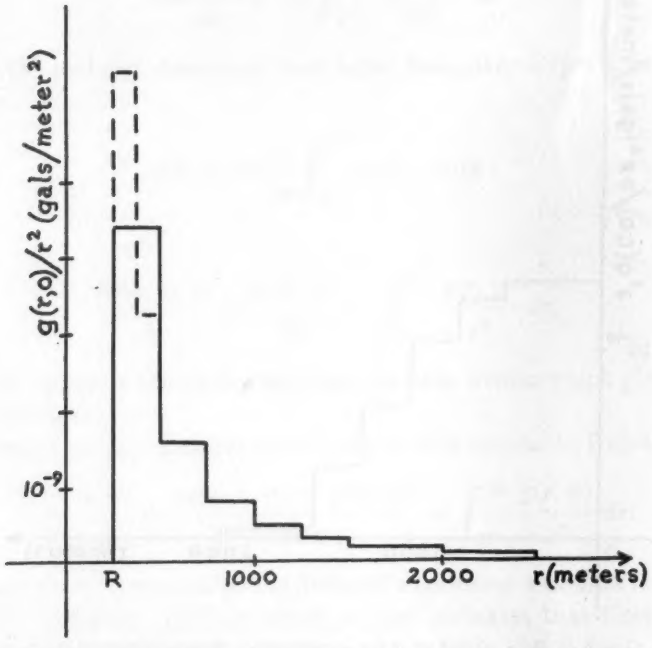

FIG. 2. Graph of $g(r, o)/r^2$ vs. r for approximate determination of $\partial g(o, o, o)/\partial z$ by Evjen's method.

that do not understand the finer points of a graphical integration. These finer points consist of the selection of R in equations (10) or (11) and the selection of the upper limit of integration in these equations.

MISCELLANEOUS COMMENTS

Baranov (1953) has given a careful treatment of a practical procedure for handling Evjen's type of calculation. It may be applied equally well to our type of computation. It is one of many possible procedures that might be employed for numerical integration (Whittaker and Robinson, 1940, p. 132–161). By using a carefully worked out integration procedure, such as Baranov's, greater accuracy can be obtained than we have sought in this note.

With regard to the question of errors the uncertainty in the second derivative is often rather severe. The error in the first derivative is a little reduced by the

averaging procedures. Since Evjen's procedure and ours represent different ways of combining the original data, it would be interesting occasionally to make the computation by these two procedures and look at the difference as a measure of uncertainty.

Skeels and Watson (1949, p. 133) have indicated how the gravitational potential may be computed. Note that our equation (4) can be written

$$U(0, 0, 0) = \frac{1}{\kappa}\int_0^\infty g(r, 0)dr. \tag{15}$$

By using this to calculate and map the potential U, we secure a map from which $\partial g/\partial z = \kappa\partial^2 U/\partial z^2$ is directly and simply calculated. This cannot be recommended as a rough procedure because of the accuracy needed in U for the computation of $\partial^2 U/\partial z^2$. However, if the U values are computed with much care this will give an averaging and smoothing operation on the data which should reduce the effect of isolated errors in g. We cannot use equation (15) unless $g(r, 0)$ vanishes rather quickly as r increases. Usually this is not the case. However, $g(r, 0)$ ordinarily approaches a fairly restricted range of asymptotic values, for various origins on the map, as r increases. The constant value of the average of these asymptotic values of $g(r, 0)$ may be subtracted from $g(r, 0)$ so that the average asymptotic value becomes zero. Then using the new reduced $g(r, 0)$'s, equation (15) can be applied.

It may be noticed that the geoid is an equipotential surface. If we assume this equipotential surface to be strictly plane over our region then, clearly as $\partial^2 U/\partial x^2$ and $\partial^2 U/\partial y^2$ are both zero over this plane, U being constant there, so $\partial^2 U/\partial z^2 = 0 = \partial g/\partial z$. The answer to this difficulty is that while the analysis above is exactly correct, the geoid is not plane. Green (1828, p. 42–45) gave the formula for the mean curvature of the geoid in terms of the vertical gradient, which can be written

$$\frac{\partial g}{\partial z} = g\left(\frac{1}{R_x} + \frac{1}{R_y}\right), \tag{16}$$

where R_x and R_y are the respective radii of curvature in the directions x and y in the tangent plane to the geoid at the point considered. By combining $\partial g/\partial z$ and g determinations with torsion balance "curvature" measurements, R_x and R_y can be separately determined so we can determine in this way the local geometry of the geoid.

The operation we carry on in the plane is to be understood as a determination of the very small variations of U in this plane. We must not assume that our plane coincides with the geoid. From U and $\partial U/\partial z = g/\kappa$ we determine the variation, of the geoid from our datum plane. Needless to say this is not a new problem (see, for example, Vening Meinez, 1934, p. 13, and Stokes, 1883, p. 168).

With regard to work on the vertical gradient of gravity, reference should be made to papers by Hofmann (1949) and by Tsuboi and Kato (1952).

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GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 155–162, 6 FIGS.

INSTRUMENTATION FOR A NEW ELECTROMAGNETIC GEOPHYSICAL FIELD TECHNIQUE, AS APPLIED IN SOUTH AFRICA*

G. FF. BELLAIRS†

ABSTRACT

The carrying out of rapid geophysical surveys by the electromagnetic method has been facilitated by the development of new apparatus, which enables the field intensity at any point to be read directly from the scale of a portable instrument.

INTRODUCTION

Sundberg (1923) and Hedstrom (1937) described a method of geophysical exploration by injecting alternating currents into the ground and measuring the resultant distribution of electromagnetic field at the surface. Guelcke (1945) described a similar apparatus employing a comparative method of measurement. Enslin (1954) has devised a simplified experimental method to make possible accurate location of narrow vertical or inclined geological structures like joints, fault-planes, mineralized fissures, and weathered dykes. The following paper describes a newer type of apparatus built to exploit Enslin's modified technique, in which the field intensities are measured by means of portable direct-reading instruments.

From the point of view of the instrument designer, Enslin's electromagnetic field technique requires solution of two associated problems:

(a) The injection into the earth, between two separated earth electrodes, of a stable alternating current of constant frequency, and

(b) The measurement by means of a portable and stable equipment of the resultant alternating field set up at various points on the earth's surface. (As a rule, only the horizontal component is of interest.)

The apparatus required for injecting the current into the ground is only required to be moved when the earth electrodes are moved, i.e. at comparatively infrequent intervals of time. It is, therefore, perfectly feasible to employ light motor transport for carrying this part of the equipment. The field intensity measuring apparatus, however, must of necessity be carried by the observer from station to station. This instrument must, therefore, be made as light and rugged as possible. The following sections describe the two sets of apparatus referred to, and show the steps taken to meet these requirements.

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THE OSCILLATOR UNIT

The oscillator unit is of comparatively conventional design, comprising a thermionic oscillator, an intermediate or buffer amplifier, and a medium-power push-pull output amplifier. The entire equipment is arranged to be energized from a 220-volt ac supply, derived from a portable gasoline-driven generating set. The generating set forms the starting point of the design, since it is desirable that the power requirements of the oscillator unit should be well within the capacity of a normal 1 kw generator set, after the usual allowances are made for the effects of high ambient temperature, high altitude, and rugged operating conditions. It was thought wise to limit the input to the oscillator unit to approximately 500–600 watts on this account, and the oscillator was therefore designed to deliver the greatest possible power output within the input limitations set.

An interesting point arises in the connection of the oscillator unit to the earth electrodes. The earth resistivities normally encountered vary considerably, and it was necessary to arrange for the oscillator to deliver its power efficiently into loads varying between 100 and 1,000 ohms. This was very conveniently achieved by means of a multi-ratio output transformer, ratios being selected by a rotary switch. The salient features of this equipment are shown by the simplified circuit diagram of the oscillator unit in Figure 1.

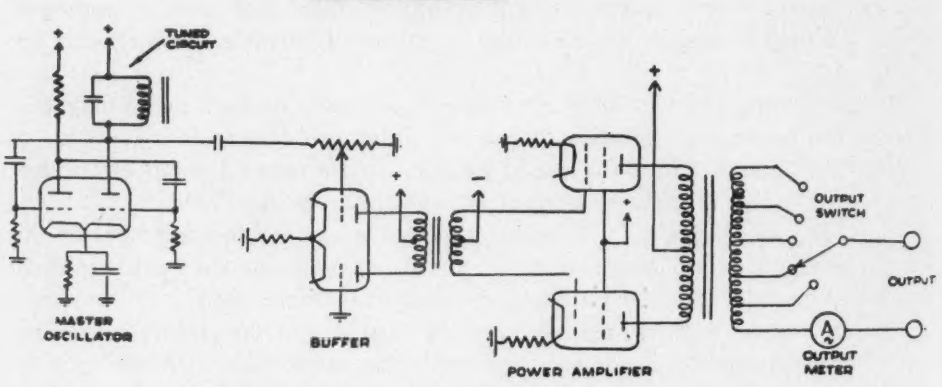

FIG. 1. Simplified circuit diagram of oscillator unit.

Anode power supplies are obtained from mercury vapour rectifier tubes, and voltage regulators are also incorporated to render the amplitude and frequency of the output of the oscillator substantially independent of small changes in generator voltage such as may be experienced when the generating plant warms up.

The frequency of the oscillator unit is pre-set at the factory, and automatic time delay switching is incorporated to ensure that the various parts of the apparatus switch themselves on in the correct sequence.

The physical construction of the apparatus was very carefully considered in

view of the arduous field conditions to be expected. The equipment is assembled on a heavy gauge, rust-proofed, steel chassis, resiliently mounted inside a ventilated steel case, through which air is blown by means of a self-contained fan to ensure proper cooling. The intake to the fan is screened to exclude insects, and particular care has been taken to ensure that the control knobs and terminals are recessed into the front of the cabinet so as to protect them from damage in transit.

Meters are provided to indicate (a) the generator output voltage, (b) the currents drawn by the tubes in the circuit, and (c) the output current delivered to the earth electrodes.

The output current obtainable with a very dry (1,000 ohm) earth is about 0.4 amp, a figure which increases as the electrode resistance falls. Output voltages

FIG. 2. Panel for oscillator unit showing control knobs and meter dials.

may be as high as 400 volts, and care is therefore necessary in handling the electrodes after the power is connected.

The overall dimensions of the oscillator unit are 29×15×20 inches and the total weight 125 lbs. The exterior of the unit is illustrated in Figure 2.

When moving the oscillator unit from one set-up to another, small variations in output current may be expected owing to variations in the resistance of individual earth electrodes. To enable field intensities taken with different set-ups to

be compared without calculation, it is necessary to keep the electrode currents at a pre-determined figure, irrespective of earth resistance. A small output level control has, therefore, been incorporated. This enables the operator to standardize the current delivered to the electrodes.

PICK-UP UNIT

A brief consideration of the field strengths obtainable at distances of several hundred yards from the earth electrode will show that it is necessary to measure strengths of less than 1 micro-gauss. Relating this field strength to the characteristics of pick-up coils of reasonable portability, it will be realised at once that alternating e.m.f.'s of the order of a few millivolts will have to be measured with stability and precision. It is therefore clearly necessary to employ thermionic amplification of the weak currents obtained from the pick-up coil to bring them

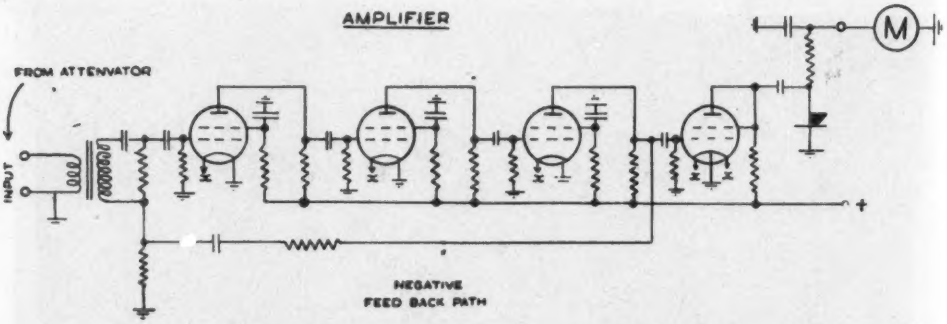

FIG. 3. Simplified circuit diagram of amplifier used with pick-up unit.

to a level at which an ordinary robust measuring instrument can be employed. The use of thermionic amplification in this way is complicated by two factors: (1) The severe limitations on weight and size of the amplifier and its dry battery power supply, and (2) the necessity for a very high degree of stability of amplification.

In fact it may be said that the practicability of building a direct-reading prospecting instrument depends entirely upon the solution of this problem. It is clearly desirable that the dry batteries used should be very small, and that the amplifier should therefore be switched off between readings at each station. This imposes the additional requirement that the amplification must not drift when the amplifier is switched on. It would be intolerable for a busy geologist to wait two minutes at each station to take a reading while the pick-up unit is "settling down."

This problem was solved by the use of a specialized type of amplifier (Black, 1934) employing negative feedback. A simplified circuit diagram of the amplifier is shown in Figure 3. It will be seen that it comprises three amplifying stages, the output of which is partially fed back in such a way as to oppose the input signal, with the results described. Following this amplifier, there is a single-tube

low-gain stage connected directly to a rectifier and to the indicating meter itself.

In order to save size and weight, the pick-up coil is wound on a wooden frame forming the framework of the entire pick-up unit. The amplifier is placed within the frame, together with its battery, the indicating meter, and the attenuator. The attenuator (see Fig. 4) consists of a chain of resistances arranged to weaken progressively the signal received from the pick-up coil. By means of a rotary

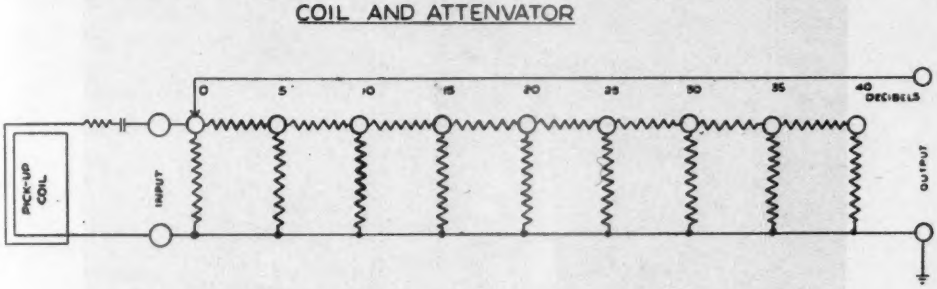

FIG. 4. Circuit diagram of coil and attennator used with pick-up unit.

switch, the amplifier can be connected to any desired point on the chain. This has the effect of extending the range of the instrument to stronger signals when the pick-up unit is employed close to one of the earth electrodes. In its current form, the attenuator covers a range of 40 decibels corresponding to a field intensity range of 100 to 1.

In order to permit the use of a very small dry battery, the filament circuits of the amplifier are connected through a mercury switch of special design, which is so arranged that the amplifier is only switched on when the entire pick-up unit is in its vertical working position. As soon as the instrument is laid on one side to be carried (Fig. 5), the mercury switch automatically switches off the amplifier and gives the battery a rest.

Owing to the negative-feed-back principle employed, the instrument gives its final reading immediately upon being switched on. In exceptional circumstances, it may be required to measure inclined or vertical components of the alternating field. Since the mercury switch would normally prevent the apparatus being used when tilted out of the vertical plane, a hand-operated spring return switch is added which enables such measurements to be taken.

Mention should be made of other minor factors, which facilitate the rapid use of the apparatus. Each pick-up unit is fitted, as shown in Figure 6, with a detachable wooden leg upon which the apparatus may be steadied while in use. A small spirit level is fitted inside the frame to ensure that the coil is in a strictly vertical plane when the readings are taken. Furthermore, a mirror mounted on the top of the coil enables the operator, while looking at the indicating meter, to "squint" readily along the top of the frame, and align it with the distant earth electrode, which is normally marked with a flag. Neglect of these precautions would produce, especially in rough country, an irregularity in observations.

FIG. 5. Pick-up unit on side for transportation between stations.

The overall stability of the equipment is about 0.1 decibels over a period of one hour. The dimensions of the pick-up unit, less the "leg," are $32 \times 21 \times 3$ inches, and the weight, including the battery, about 12 lbs.

Operation of the pick-up is straightforward, the procedure being:

(1) Set up the instrument and align it visually on the flag marking the earth electrode.

(2) Turn the attenuator knob until a convenient deflection is obtained on the meter.

(3) Read the decibels directly off the meter scale and add the attenuator reading. Note the result in the field work-book.

(4) Move on to the next station.

It will be appreciated that two or three pick-up units may be used simultaneously by independent observers if it is desired to save time in surveying a given area.

FIG. 6. Pick-up being set into place for reading.

Despite the necessity for employing very light and small components in the construction of the pick-up unit, field experience has shown that they are reliable and that a battery life of many months may be obtained even when the equipment is being used every day.

A number of sets of equipment has been constructed for operation on different frequencies, and work is still proceeding to ascertain which frequency or combination of frequencies gives results which are most easily interpreted. It has not been thought desirable to attempt to build multi-frequency equipment at the present time, and it is not proposed to introduce such a complication unless a clear case is found for doing so. To date this appears unlikely.

ACKNOWLEDGMENTS

The author wishes to acknowledge the ready help and advice given to him by Dr. J. F. Enslin and officers of the Geological Survey of the Union of South

Africa, at whose suggestion this equipment was developed; he is indebted to the Directors of F. G. Slack & Co. (Pty.) Ltd. for permission to publish this paper.

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PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,684,468. C. D. McClure and R. L. Mills. Iss. 7/20/54. App. 8/21/50. Assign. Socony-Vacuum Oil Co., Inc.

Apparatus for Measuring a Periodically-Recurring Signal in the Presence of Random Noise. A system for improving signal-to-noise ratio for a periodically-recurring signal by recording the original signal, reproducing the signal with a fixed time delay, and combining the reproduced signal with the original signal in phase coincidence.

U. S. No. 2,685,058. W. J. Yost. Iss. 7/27/54. App. 8/27/49. Assign. Socony-Vacuum Oil Co., Inc.

Geophysical Exploration by Electric Pulses. An electrical prospecting system using two current electrodes energized with commutated rectangular pulses and two pick-up electrodes whose potential is momentarily measured at various phase positions after initiation of the current pulse.

U. S. No. 2,690,537. O. Weiss and L. Massé. Iss. 9/28/54. App. 7/10/50. Assign. Weiss Geophysical Corp.

Electrical Method and Apparatus for Geological Exploration. A method of electrical prospecting in which a-c of two frequencies is applied to the ground and the modulation-frequency signal explored by comparing its phase as picked up at pairs of electrodes along the profile, or observing variation in amplitude of the modulation component when a seismic pulse or a d-c current pulse is superimposed on the ground.

MAGNETIC PROSPECTING

U. S. No. 2,684,465. O. H. Schmitt. Iss. 7/20/54. App. 4/18/44. Assign. U. S. A.

Detection System. A detecting system for a flux-valve magnetometer in which the series of alternating positive and negative pulses are converted into a signal proportional to the difference in their amplitudes by using balanced demodulators with separate cathode followers, filters, and phase inverters having a common cathode resistor but with separate plate loads across both of which the output is taken.

U. S. No. 2,687,507. E. O. Schonstedt. Iss. 8/24/54. App. 9/29/50.

Method and Apparatus for Measuring the Earth's Total Magnetic Field Vector. A self-oriented total-field airborne magnetometer which also records the orientation of the measuring element with respect to the vertical and with respect to the aircraft axis by means of potentiometers attached to the gimbals.

U. S. No. 2,689,333. D. G. C. Hare. Iss. 9/14/54. App. 3/31/44. Assign. U. S. A.

Magnetic Stabilization System. A stabilization system for a self-orienting airborne magnetometer in which the output of the orientation-detecting elements is converted to d-c which controls the amplification of tubes supplied with a-c in quadrature and whose output drives two-phase orienting motors.

* Gulf Oil Corporation, Patent Department, Pittsburgh, Pa.

SEISMIC PROSPECTING

U. S. No. 2,683,414. R. L. Klotz, Jr. Iss. 7/13/54. App. 5/7/47. Assign. Seismograph Service Corp.

Arrangement to Insure Complete Detonation of Explosive Charges. A seismograph charge made up of a column of separate explosive cartridges each of which has a cavity which forms an explosive jet and insures detonation of the adjacent cartridge.

U. S. No. 2,683,867. J. O. Vann. Iss. 7/13/54. App. 6/11/51.

Parachuted Radio Seismic Transducer. A vibrometer having an arm suspended on a horizontal torsion wire and carrying a powdered iron core adjacent to the tank coil of a radio transmitter fixed to the base so that relative vibration of the core and coil varies the frequency of the transmitted radio signal.

U. S. No. 2,685,251. C. O. Davis, H. A. Lewis, and G. A. Noddin. Iss. 8/3/54. App. 12/17/47 and 5/27/49. Assign. E. I. du Pont de Nemours & Co.

Method of Blasting. A method of underwater blasting using a number of separate charges only one of which has an electric detonator and the others having pressure-sensitive detonators which are fired by the pressure wave from the first charge.

U. S. No. 2,687,092. B. F. Duesing. Iss. 8/24/54. App. 2/26/51.

Protective Device for Blasting Cartridges. A loading device for seismograph shot holes having a cup which surrounds the top of the charge with a number of vertical supports for a platform above the charge which protects the top of the charge and its primer.

U. S. No. 2,687,093. H. W. Botts. Iss. 8/24/54. App. 9/23/49. Assign. Hercules Powder Co.

Explosive Device. An explosive cartridge which can be screwed to similar cartridges to form an explosive column, the edge of the threads having a small angle so that tension in the column causes the threads to stick, which prevents unscrewing.

U. S. No. 2,688,124. W. E. N. Doty and J. M. Crawford. Iss. 8/31/54. App. 2/27/53. Assign. Continental Oil Co.

Method of and Apparatus for Determining Travel Time of Signals. A seismic prospecting system in which the frequency of a continuous-wave source is slowly varied and the picked-up vibration is multiplied by a delayed counterpart of the transmitted vibration and the product integrated over a short period and recorded, the multiplication and integration being made for various time delays to determine the delay which yields the maximum integration value.

RADIOACTIVITY PROSPECTING

U. S. No. 2,686,266. R. W. Pringle, K. I. Roulston, and G. M. Brownell. Iss. 8/10/54. App. 11/10/49 and 1/12/50.

Improvement in Radiation Detectors. A radioactivity detector having a single conical scintillating crystal with reflecting shield which also prevents moisture deterioration and cemented to a photomultiplier tube whose output is fed to a univibrator and rate meter.

WELL LOGGING

U. S. No. 2,682,800. G. H. Ennis and W. W. Ennis. Iss. 7/6/54. App. 8/25/51. Assign. Robert V. Funk.

Photoelectric Water Locating Instrument. A water-locating device for wells in which a light-absorbing dye is automatically injected into the well fluid during the first traverse by the instrument and the fluid transparency measured photoelectrically during a second traverse.

U.S. No. 2,685,798. R. W. Goble. Iss. 8/10/54. App. 5/15/47. Assign. Eastman Oil Well Survey Co.

Apparatus for Measuring and Indicating Various Conditions Such as Temperature and Pressure. A system for simultaneously recording temperature and pressure in a well over a single-conductor cable in which positive and negative pulses are generated whose respective repetition rates indicate the variable and the frequencies of the respective pulses are recorded at the surface.

U. S. No. 2,686,268. P. W. Martin and R. W. Pringle. Iss. 8/10/54. App. 8/10/51.

Well Logging Device. A radioactivity logging apparatus having a source of beamed neutrons and a scintillation counter with temperature control.

U. S. No. 2,686,881. G. Herzog and A. S. McKay. Iss. 8/17/54. App. 3/23/51. Assign. The Texas Co.

Measuring Absolute Radioactivity of Borehole Formations. A method of measuring absolute radioactivity of formations penetrated by a borehole by logging the hole with a counter-type meter, separately measuring the activity of the mud, casing, and cement, and subtracting these counts from the count observed in logging.

U. S. No. 2,688,095. J. H. Andrews. Iss. 8/31/54. App. 6/3/53.

X-Ray Camera for Underground Geological Exploration. An apparatus for making a picture of penetrating radiation from a borehole wall and having a directional filter, scintillation crystal, and photomultiplier which are rotated about the axis of the borehole, the output signal activating a glow tube whose light is focused on a synchronously-moving film.

U. S. No. 2,688,115. A. B. Hildebrandt. Iss. 8/31/54. App. 10/8/52. Assign. Standard Oil Development Co.

Open Sleeve Electrode Assembly for Well Logging. An electric logging electrode system having a flexible sleeve of insulating material with springs which press its top and bottom edges against the borehole wall and electrodes on the outer surface of the sleeve insulated from the mud inside the sleeve.

U. S. No. 2,688,703. H. J. Di Giovanni, R. T. Graveson, and A. H. Yoli. Iss. 9/7/54. App. 5/26/52. Assign. U. S. A.

Radioactive Logging Apparatus. Radioactivity logging apparatus using a crystal scintillometer whose pulses are transmitted to the surface, converted into rectangular pulses, and their rate indicated.

U. S. No. 2,688,871. A. Lubinski. Iss. 9/14/54. App. 1/3/49.

Instantaneous Bit Rate of Drilling Meters. A drilling rate recorder having a weight measuring element in the dead line which records the rate of change of weight on the bit.

U. S. No. 2,688,872. R. E. Hartline and J. D. Eisler. Iss. 9/14/54. App. 6/8/49. Assign. Stanolind Oil and Gas Co.

Apparatus for Fluid Entry Logging. A device for separately determining water and oil produced by a well having packers at the top and bottom of the producing interval connected by tubing with a port for releasing water through a magnetic-vane flowmeter which generates a-c in a circuit and also having electrodes outside the tubing with which the water-oil interface in the annular space may be detected.

U. S. No. 2,689,144. L. V. Uhrig and J. N. Atkins, Jr. Iss. 9/14/54. App. 10/20/50. Assign. Standard Oil Development Co.

Seal for Borehole Thermometer Piston Rods. A seal for a pressure-equalized recording-type mercury

thermometer in which thermal expansion of the mercury moves a rod through the seal to actuate the stylus of the recorder.

U. S. No. 2,689,329. C. W. Zimmerman. Iss. 9/14/54. App. 10/12/50. Assign. Socony-Vacuum Oil Co., Inc.

Dielectric Well Logging System. A dielectric logging sonde having pairs of insulated parallel rods forming a condenser whose electric field extends into the formation and connected to a coil to form a high-Q circuit connected to a phase discriminator network for measuring changes in resonance or Q of the circuit.

U. S. No. 2,689,918. A. H. Youmans. Iss. 9/21/54. App. 4/26/52. Assign. Well Surveys, Inc.

Static Atmosphere Ion Accelerator for Well Logging. A neutron source for well logging using a sealed tube containing deuterium at low pressure with electrons from a filament accelerated to ionize the deuterium and the deuterium ions accelerated to strike a zirconium target on which tritium has been adsorbed.

U. S. No. 2,690,468. H. Faul and R. J. Smith. Iss. 9/28/54. App. 4/4/47. Assign. U. S. A.

Drill Hole Logging Probe. A cable entry assembly for the top of a logging probe in which the cable passes through packing in a tapered packing chamber, the cable shield clamped by tapered dogs, and the conductor connected to an insulated thimble.

MISCELLANEOUS

U. S. No. 2,683,563. B. D. Lee and G. Herzog. Iss. 7/13/54. App. 5/14/49 and 7/8/50. Assign. The Texas Co.

Method of Operating Potentiometric Models. A potentiometric model in which interfaces are simulated by an insulating barrier with conducting segments molded in or with a number of surface electrodes whose opposite members are connected by wires over the edge of the barrier so that the barrier is not necessarily an equipotential surface.

U. S. No. 2,685,038. R. L. Hoss. Iss. 7/27/54. App. 5/8/51.

Method of and Means for Measuring the Depth of Penetration of Bullets within Subsurface Formations. A perforating gun which fires projectiles carrying a definite amount of radioactive material and having a radiation-intensity meter in the gun.

U. S. No. 2,686,108. W. S. Hoffmeister. Iss. 8/10/54. App. 8/10/51. Assign. Standard Oil Development Co.

Microfossil Prospecting for Petroleum. A process for locating ancient shore lines by taking samples from wells from formations having the same geologic time, digesting aliquot samples with hydrofluoric acid, and mounting the residue on microscope slides from which the microfossil population is determined.

U. S. No. 2,686,425. H. W. Dietert. Iss. 8/17/54. App. 9/2/52. Assign. Harry W. Dietert Co.

Permeameter. A gas-flow permeameter having a motor-driven fan which flows air in series through a fixed orifice and the porous sample, the pressure drop across the sample being measured with a manometer.

U. S. No. 2,689,943. F. Rieber. Iss. 9/21/54. App. 3/28/46. Assign. The Vibrotron Co., Ltd.

Frequency Determining Unit. A frequency-measuring device in which the signal is passed through a tungsten wire in a transverse magnetic field and the tension of the wire adjusted for resonance, the wire being mounted to compensate temperature variations and forming part of a sharply-tuned bridge circuit.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE THIRD QUARTER OF 1954

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2,682,766	12, 140	2,684,810	148	2,686,676	224
2,682,798	324	2,685,027	308	2,686,706	324
2,682,800[a]	508	2,685,035	236	2,686,845	224
2,683,038	224	2,685,038[a]	304, 48	2,686,846	224
2,683,111	324	2,685,041	12	2,686,847	484
2,682,220	416	2,685,058[a]	132	2,686,858	324
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2,683,222	308	2,685,204	288	2,687,035	188
2,683,224	148	2,685,206	16	2,687,036	168
2,683,234	308	2,685,207	16	2,687,041	188
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* A key to the subject classification system will be found in GEOPHYSICS, v. XII, p. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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Physical Meteorology, by John C. Johnson; published jointly by the Technology Press of the Massachusetts Institute of Technology and John Wiley & Sons, Inc., New York, 1954, 393 pp.

This book is designated by the author as "a study of those meteorological phenomena, not directly concerned with the circulation of the atmosphere, which link meteorology with other branches of science."

While it is intended as a fairly advanced text in the physics of the atmosphere, the geophysicist will find valuable sections on refraction of light and microwave radiation by the atmosphere, visibility, radiation transfer, radar meteorology, and atmospheric electricity. The discussion of cloud and precipitation processes and "rainmaking" should be of general interest. And, of course, for the scientist whose children and friends expect him to know all about all things natural, there are authoritative treatments of lightning, thunder, rainbows (single and multiple), halos, coronas, mirages, and all the other atmospheric phenomena that present themselves to the observing eye and inquiring mind.

The section on atmospheric acoustics is unfortunately rather cursory but this deficiency is more than compensated for by the excellent bibliographies found at the end of each chapter. Rather than being mere guides to further reading for the beginning student, the references are expressly chosen to assist the research worker in bordering fields.

The reviewer has adopted this book as the text for his courses in physical meteorology.

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Petroleum Microbiology, by Ernest Beerstecher, Jr., Elsevier Press, Inc., New York, 1954, 352 pp., $8.00.

This book was written to interest bacteriologists in the very new and promising field of petroleum microbiology. The author discusses the various facets of the petroleum industry in which microorganisms play a conspicuous role. Some of these are: the role that microbiology plays in geological processes, such as in the biogeochemistry of calcium, silicon, iron, sulfur, nitrogen, phosphorus, and carbon; the role that microorganisms play in the synthesis of petroleum; the use of microorganisms in petroleum exploration; the activities of microorganisms in drilling muds, in petroliferous formations, and in corrosion; and the use of microorganisms as reagents in the manufacture of petroleum products. In each of these specific applications the author summarizes the existing literature and presents an ample bibliography.

The chapter on the use of microorganisms in petroleum exploration is the only part of the book that would interest geophysicists. In this chapter the author presents the two basic assumptions for the success of the microbiological prospecting method; namely, that gas emanations reach the surface from a reservoir at depth, and that microorganisms exist which give a distinctive observable response to these emanations.

Geochemists have theorized that the passage of gaseous emanations through the surface should cause some chemical change to take place at or near the surface, but they have been unsuccessful thus far in showing that such changes generally exist. Gas seeps associated with shallow reservoirs are observable and many geochemists feel no reluctance in assuming that there will be seepage no matter what the reservoir depth. They merely consider that the amount of seepage reaching the surface will be less for deeper reservoirs. Assuming this to be correct, if the emanations from deep reservoirs are to be observed, the method of detecting hydrocarbons must become more sensitive. At present physical methods can detect hydrocarbons to a tenth of a part per million while present microbiological methods are limited to a range from 1 to 10 parts per million. The author is optimistic about the potentialities of improving this lower limit of sensitivity of the microbiological methods and has suggested several ways in which such improvement may be accomplished.

The greatest encouragement to the microbiological method has been Davis's work on paraffin dirt. Davis has shown that paraffin dirt is the result of the utilization of hydrocarbons by microorganisms. The author considers this evidence proof of the second assumption upon which the microbiological method of exploration is based. He does not mention the possibility of using carbon 14 measurements on hydrocarbons taken from the soil to substantiate the first basic assumption.

The bulk of the last chapter is concerned with a critical review of the patents that have been published on the use of microorganisms for petroleum exploration.

PAUL WUENSCHEL

"Study of Some Phenomena Foretelling the Occurrence of Destructive Earthquakes," by Eiichi Nishimura, *Disaster Prevention Research Institute*, Bull. No. 6, October 1953, Kyoto University, Kyoto, Japan, 63 pp.

This paper is a progress report on research which is directed toward discovering any phenomena that would foretell the occurrence of destructive earthquakes.

Currently four separate approaches are under investigation.

The first is a continuous recording of the tilt of the earth's surface. Previously, repetitions of precise leveling into an epicentral area after the occurrence of a destructive earthquake indicated that

there was definite upheaval and subsidence of the earth's surface centered about the epicenter. To determine if the earth movement was discernible prior to an earthquake, several tiltmeter stations were established throughout Japan. Thus far some success has been obtained, for if the epicenter is within one hundred kilometers of a station, the tiltmeter can detect a minute tilting of the ground (less than 0.5 inch) that precedes the earthquake by a time interval ranging from several hours to several months. Some, but not all, of the tilting motions began by a tilt toward the epicenter prior to the earthquake followed by a tilt away from the epicenter after the earthquake. Even in the case of distant earthquakes a disturbance has been noted which appears on several tiltmeters simultaneously and always has the same polarization. Thus far sufficient data are not available to discuss the mechanism of these disturbances.

The second approach is based on a local (in the sense of scores of kilometers) change in the geomagnetic declination that has been observed in one instance to precede a destructive earthquake by one month. The observation station was within forty kilometers of the epicenter. Additional stations have been established and the three components of intensity and the declination are to be recorded.

The third approach is the detailed study of the structure of the earth's crust under Japan by using weak aftershocks as an energy source. Thus far, the instruments for this work have been constructed but no measurements have been reported. The instrument is a vertical-component seismograph whose pendulum period is $\frac{1}{2}$ second, galvanometer period is $\frac{2}{3}$ second, and overall magnification is approximately 90,000.

The fourth approach is based on a chance observation of a sudden increase of the radon content of the soil gas that occurred two and one half hours before a large earthquake. The epicenter was 150 kilometers from the observation point. Geiger counters and electroscopes are being used for further measurements. No success has been reported in repeating this observation.

In all four projects, the quantities measured are small and continuous observation is essential over long intervals of time. The ability to develop instrumentation that can give both sensitivity and stability has thus far been a limiting factor. The choice of station site is critical, for it has been necessary to install the instruments in subterranean rooms from one hundred to three hundred meters below the surface.

PAUL WUENSCHEL

"Beiträge zur Fehlertheorie der Schwerereduktion von Nivellements (Contributions to the theory of errors for the gravity reduction of leveling)," by Karl Ramsayer. *Sonderhefte der Zeitschrift für Vermessungswesen*, no. 1, 31 pp. Stuttgart, Verlag Konrad Wittwer, 1954.

This publication is being noted here for two reasons. One is to bring to attention the start of a new series of scientific publications, *Sonderhefte der Zeitschrift für Vermessungswesen*, supplementary numbers of the periodical *Zeitschrift für Vermessungswesen* (Journal of Surveying), in which are to appear contributions which fall outside the limits of the journal either because of their length or their content.

The second is to note the use and value of gravity data in a field which at first sight seems unlikely, that of precision leveling. The connection between gravity and leveling arises on the one hand from the fact that differences of potential can be found by integrating, with respect to height, the vertical component of gravity, while on the other hand the very definition of "level" is tied in with surfaces of equal potential.

Since this subject is a rather special one, the article will be reviewed here only by giving a translation of the abstract:

"The errors of the gravity reduction for leveling, which arise from the gravity and elevation errors of the gravity stations and from the deviations of the true elevation and gravity profiles from the corresponding approximating chord polygons for the gravity stations, are investigated theoretically and empirically for various station spacings."

THOMAS A. ELKINS

Bulletin of the Geological Survey of Great Britain, no. 6. London, Her Majesty's Stationery Office, 1954. iv+56 pp., price 5s.6d.

This paper-bound publication is devoted to gravity and magnetic interpretation and contains five articles:

I. "A gravitational survey over a concealed portion of the Warburton Fault near Lymm, Cheshire," by W. Bullerwell, pages 1–12.

II. "A gravimeter survey over the Tilmanstone Fault, Kent Coalfield, by W. Bullerwell," pages 13–20, Plates I–II.

III. "A vertical force magnetic survey of the Coalisland District, Co. Tyrone, Northern Ireland," by W. Bullerwell, pages 21–32.

IV. "The least-squares method of determining regional contours," by L. H. Tarrant, pages 33–35.

V. "A gravimeter survey of the Ston Easton–Harptree District, East Somerset," by W. Bullerwell, pages 36–56.

Paper I describes a survey made with a small Süss double-beam Eötvös torsion balance in September, 1947. A qualitative interpretation is given. Paper II presents profiles made in April, 1949 with a Frost-type gravimeter at an average station spacing of about 800 feet. A quantitative interpretation is given, based upon calculations for assumed graben-type structures. Paper II describes a Watts vertical force variometer areal survey at 1500-foot spacing made in March, 1949. It is stated that a gravimeter survey would be a useful supplement.

Paper IV explains a method of computing the regional by fitting a second-degree polynomial in two variables by least squares. A postscript states that the paper was prepared before the publication of the article by W. B. Agocs, "Least squares residual anomaly determination," GEOPHYSICS, v. XVI, pages 688–696 (1951).

Paper V presents an areal survey with 5 to 6 stations per square mile, started in July, 1949 and made with a Frost-type gravimeter. The method of paper IV was used to determine the regional here. In fact four different regionals based on four different selections of points were computed. Two selections used nine points each, the other two twelve points each. That regional was selected which gave the least sum of squares of differences between observed and regional values at 63 points regularly spaced over the survey. This was one of the twelve-point regionals. This paper contains many remarks on the correction and interpretation of gravity data which will be of value to all gravity interpreters.

THOMAS A. ELKINS

"Rock Magnetism and the Earth's Magnetic Field during Paleozoic Time," by John W. Graham, *Journal of Geophysical Research*, Vol. 59, No. 2, pages 215–222, June, 1954.

This summary of three and a half years' work on rock magnetism at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, will be of great value to all those who are interested in the controversial question of possible major changes in the direction and intensity of the earth's magnetic field. Publication of the full details is promised for the near future.

Briefly stated, the author's point is that measurements of the magnetic properties of samples from the northeastern United States lead one to the conclusion that the earth's magnetic field preserved essentially the present orientation and direction during most of Paleozoic time, except for possible local and rapid changes of short duration. He believes that sufficient data regarding the phenomenon of inverse polarization are now known that the burden of proof is on any proponent of reversals in the direction of the earth's magnetic field.

The paper is easy and interesting reading because it is the manuscript presented orally at an informal conference at the Institute of Geophysics, University of California. This reviewer believes that its publication is a worthwhile innovation. More such examples in the geophysical literature would be welcome.

THOMAS A. ELKINS

"Biochemical Investigations in Finland," by Vladi Marmo, *Economic Geology*, Vol. 48, No. 3, May, 1953, pages 211–224.

The author evaluates a geochemical and biochemical technique as an aid to mineral exploration for copper, nickel, zinc, and molybdenum in Finland. Three areas of sulfide mineralization were studied. In the first area, correlations of the following kinds were obtained: between a low pH of well waters and sulfide mineralization near the wells; between copper and zinc mineralization in the bed rock and the copper and zinc concentration in the ground water saturating the bed rock; and, finally, between the copper and zinc concentration in the ash of leaves of certain plants common to the area and the copper and zinc concentration in the ground water. In the second area, a different species of plant was sampled, but the same correlations were observed. In the third area, molybdenum and copper mineralization occurring as disseminations in a granite granodiorite below three to seven meters of bog were detected by the analysis of the ash from leaves and twigs of a plant that was common to the prospect area.

The author adds a word of caution when applying these techniques. The leaf analysis method is too sensitive at times. Relatively high metal concentrations are found in some plants over ground that is very weakly mineralized, and further, the relationship between the metal content of the plant and the metal content of the ground in which it grew is not linear. Some plants reach a saturation concentration for a particular metal even when this metal has a relatively low concentration in the ground water.

The author considers these techniques ideal as an aid in the interpretation of geophysical anomalies by indicating whether metals of value are responsible for the anomaly, or whether the anomaly is due to non-economic concentrations of pyrrhotite or graphite.

PAUL WUENSCHEL

"Studio Geoelettrico dell'Idrologia Sotterranea del Friuli Orientale, Parte 1ª—La zona tra Pieris e Monfalcone," by Ferruccio Mosetti; *Tecnica Italiana*; *Revista d'Ingegneria e Scienze*, Trieste, April–May, 1954.

The author reports on an investigation for the location of water-bearing areas in the region of Montefalcone, in the Isonzo Valley, some twenty miles northwest of Trieste. The work consisted of electrical resistivity measurements using techniques both of horizontal profiling and vertical soundings. In this area, two sorts of alluvial sediments are present: impervious conductive clays, and porous sands and gravels which are more resistive than the clays. The problem of differentiating both formations is amenable to electrical prospecting. The author comments on the field results and supports them by laboratory tests. This is a compact and interesting article, five pages in length.

E. G. LEONARDON

"Su Alcune Ricerche Geoelettriche di Zone Mineralizzate," by Ferrucio Mosetti, *L'Industria Mineraria*, December, 1953.

The author shows how a mineral mass or fracture or ore body may be located by resistivity measurements, provided that the electrical resistivity of the encasing rocks be decidedly and sufficiently different from that of the mass under consideration. This is illustrated by resistivity profiles carried out first on a bauxite deposit; second, on different mineralized occurrences (conductive sulphides). The article, which is clear and makes good reading, is three pages long.

E. G. LEONARDON

"Gravity Measurements Along the Lines of Precise Levels throughout Japan, by means of Worden Gravimeter," by Chuji Tsuboi, Akira Jitsukawa and Hirokazu Tajima, *Proceedings of the Japan Academy*.

"Gravity Surveys Along the Lines of Precise Levels throughout Japan by means of a Worden

Gravimeter," by Chuji Tsuboi, and others, *Bulletin of the Earthquake Research Institute, Toykyo University*, Supplementary Vol. IV, Part I, Aug., 1953, and Part II, March, 1954.

Of these two series of papers, the first are in the nature of preliminary reports, the second of final reports on regional gravity surveys in Japan.

The *Proceedings* papers are as follows:

Part I: Vol. 29 (1953), No. 6, pp. 235–238, Shikoku Island; 276 gravity stations.

Part II: Vol. 29 (1953), No. 7, pp. 311–315, Chugoku District (west end Honshu Island); 420 stations.

Part III: Vol. 29 (1953), No. 7, pp. 316–320, Kinto District (southwestern Honshu Island); 480 stations.

Part IV: Vol. 29 (1953), No. 9, pp. 503–508, Tohoku District (northwestern Honshu Island); 667 stations.

Part V: Vol. 29 (1953), No. 10, pp. 550–555, Chubu District (west central Honshu); 748 stations.

Part VI: Vol. 29 (1953), No. 10, pp. 556–560, Cantu District (central Honshu Island); 366 stations.

The measurements were made with a Worden gravimeter and all are along lines of precise levels. The station interval along the lines is around 3 km and the spacing between lines is mostly between 20 and 50 km. The surveys have given regional coverage of most of the main island of Japan (Honshu) and of Shikoku.

Each of the six Parts contains two small-scale (one page) maps, one showing the lines of precise levels and district boundaries and the other showing the gravity station locations along the level lines and Bouguer anomaly contours at 5 mg interval. There are brief discussions of the principal anomalies shown and their relation to major geologic features.

The Earthquake Institute publication contains three reports:

Part 1. Shikoku District, Vol. IV, Part I, Aug. 1953 (pp. 1–44).

Part 2. Chugoku District, Vol. IV, Part II, Mar. 1954) (pp. 48–115).

Part 3. Supplement to Shikoku report, Vol. IV, Part II, Mar. 1954 (pp. 117–123).

For each of these parts there is a map at scale 1/500,000 of Bouguer anomalies. For parts 2 and 3, the maps are colored with contours in red over positive areas and blue over negative areas and values are shown at each station.

The Earthquake Research Institute publications contain a history of the project, detailed discussion of the instrument, the methods of measurement and reduction of results, and extensive tables of data from the measurements. There are some discussions of the relations of gravity anomalies to the regional geology and to centers of earthquake activity. The program anticipates very careful determination of gravity differences between especially selected stations with the idea of repeating these gravity measurements over periods of many years to detect any time variations in gravity that may accompany earthquake activity.

The reports, in their present form, give useful information on regional gravity in the several sections of Japan which are covered. Presumably at some later time, these sections will be assembled on a smaller scale map to show relations between the segments now reported.

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Houston, Texas

PUBLICATIONS RECEIVED

American Journal of Science, v. 252, nos. 9 & 10. (Sept & Oct., 1954)
Annales de Geophysique, v. 10, no. 2 (April & June, 1954)
Annali di Geofisica, v. 6, no. 1 (January, 1954)
Beihefte zum Geologischen Jahrbuch, volumes 10, 11 & 14.
Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 6, nos. 5–6 & 7–8 (May–June &July–Aug., 1954)
Bulletin of the Earthquake Research Institute, v. 22, no. 1–2 (March, 1954)
Bulletin of the Seismological Society of America, v. 44, no. 3 (July, 1954)
Butsuri-Tanko, v. 6, nos. 3 & 4 (1953)
Deutsches Hydrographisches Institut Jahrbuch, v. 8 (1953)
Economic Geology, v. 49, no. 5 (August, 1954)
Erdöl und Kohle, v. 7, nos. 7, 8 & 9 (July, Aug. & Sept., 1954)
Geological Abstracts, v. 2, no. 3 (1954)
Geophysical Abstracts, v. 157 (April & June, 1954)
Geophysical Prospecting, v. 2, no. 3 (Sept., 1954)
Journal of Geophysical Research, v. 59, no. 3 (Sept., 1954)
Precambrian, v. 27, nos. 7, 8, 9 & 10 (July, Aug., Sept. & Oct., 1954)
Quarterly Journal of the Geological Society of London, v. 110, part 1 (Sept. 29, 1954)
Science, v. 120, nos. 3109–3120 (July 30–Oct. 15, 1954)
Science Reports of the Tohoku University, 5th Series, Geophysics, v. 5, no. 3 (Dec., 1953)
Scientific Monthly, v. 79, nos. 3 & 4 (Sept. & Oct., 1954)
Tellus, v. 6, no. 2 (May, 1954)

NEW BOOKS RECEIVED

Ridenaur, Louis N., 1954, *Physics for the engineer:* New York, McGraw-Hill Book Co., Inc.
Stevenson, K. M., 1954, *Handbook on uranium prospecting in South Australia:* Adelaide, Department of Mines of South Australia

GEOPHYSICS, VOL. XX, NO. 1 (JANUARY, 1955), PP. 176–177, 1 FIG.

MEMORIAL

WESLEY HUBERT SEIFERT

Wesley Hubert Seifert died suddenly in his home on the morning of February 23, 1954. He lived at 437 N. W. 46th Street in Oklahoma City, Oklahoma. His sudden passing was indeed a great shock to his family and many friends.

Wesley was born in Stroud, Oklahoma, on March 9, 1900, where he was reared and graduated from high school. He attended Oklahoma University, where he graduated in 1923, receiving a degree of Bachelor of Science in Electrical Engineering.

After graduation from college Wesley was employed by Oklahoma Gas and Electric Company of Oklahoma City as Valuation and Cost Estimating Engineer. In 1931 he was advanced to Chief Electrician and Assistant Chief Engineer at the Huey Power Station, which position he held until June, 1933. In July, 1933 he was employed by Geophysical Research Corporation on a seismograph crew. In May of 1937 Wesley started to work for Magnolia Petroleum Company as Assistant Interpreter on a seismograph crew. He was promoted to Seismograph Party Chief in 1943, and to Supervisor in 1948, which position he held at the time of his death.

It was always amazing to many of us that Wesley started in a new profession at the age of 33 after spending 10 years in the utility business, and in which he had a very successful career. Due to the depression of the late 20's and early 30's he lost his position with the Oklahoma Gas and Electric Company. It was at this time that he went into geophysics in competition with much younger men who were just out of college. Due to his ability and application, he succeeded in the new profession and rose to the position of Supervisor of Seismic Exploration with a wide experience in field operations and interpretations.

Wesley was a very devout member of the Christian Science Church. He was a student of human psychology and would go to great lengths in an effort to help a young man, both technically and in his human relations. Wesley loved his home and spent a great deal of time with his flowers and garden. He liked sports of all kinds, but his main hobbies were hunting and fishing. He also loved to play golf, bowl, and tinker with "gadget fixing."

Wesley is survived by his wife, Bertha V. Seifert; his mother, Mrs. Rebecca Seifert, Midland, Texas; a sister, Mrs. W. R. Gayley of Cushing, Oklahoma; and three brothers, Lee H. Seifert of Wichita, Kansas; J. L. Seifert of Perry, Oklahoma; and Ray E. Seifert of Midland, Texas.

Everyone with whom Wesley associated enjoyed his humor, enthusiasm, and good will. Few men pass our way who have left more pleasant memories.

PAUL E. NASH

CONTRIBUTORS

GUY FF. BELLAIRS

GUY FF. BELLAIRS was educated at Dulwich College and London University, where he graduated in 1937.

He was engaged on carrier telephony at the Research Station of the British Post Office when war broke out. From 1939 to 1946 he served with the Royal Signals, mainly as a communications engineer in military guise.

Civilian life in post-war England proved frustrating, but the timely sale of various patent rights helped him to escape to South Africa in 1947. He is now a director of an electrical engineering business, and devotes most of his time to developing new ways of applying electronics to the mining field. He is a member of the Institution of Electrical Engineers.

DAVID BUDENSTEIN, after graduating with distinction from Girard College, Philadelphia, Pa., continued his education at The Pennsylvania State University. He received his Bachelor of Science degree in the field of geophysics in June, 1952 and his Master of Science degree in the same field in February, 1954. While an undergraduate, he was elected to Sigma Gamma Epsilon, mineral industries honorary of The Pennsylvania State University,

At the present time Budenstein is serving with the United States Army as a physicist at the White Sands Proving Grounds, New Mexico. Formerly, he was a member of the aeromagnetic branch of the U. S. Geological Survey in Washington, D. C.

DAVID BUDENSTEIN

D. B. ERICSON

D. B. ERICSON received the B.S. Degree in geology from the Massachusetts Institute of Technology in 1931, and the M.S. in geology and paleontology from the California Institute of Technology in 1933. From 1934 to 1938 he worked as field geologist for various petroleum companies in California and Texas. In 1938 he went to Turkey for two years to prospect for petroleum in Asia Minor for the Petrol Grubu of the Maden Tetkik ve Arama Enstitusu of the Turkish Government. From 1943 to 1945 he was assistant state geologist with the Florida Geological Survey. In 1945 he took up research in recent marine sediments at the Woods Hole Oceanographic Institution, and in 1947 he took part in the first Mid-Atlantic Ridge expedition of the *Atlantis* under the direction of Maurice Ewing. Since then he has been research associate in marine geology at the Lamont Geological Observatory of Columbia University.

He is a member of the American Geophysical Union and the Society of the Sigma Xi.

WILLIAM MAURICE EWING

WILLIAM MAURICE EWING received the B.A. degree with Honors in mathematics and physics in 1926, the M.A. in 1927, and the Ph.D. in 1931, all from The Rice Institute. He was Hohenthal Scholar from 1923 to 1926 and Fellow in Physics at The Rice Institute from 1926 to 1929. During the school year 1929–1930 he was Instructor in Physics at the University of Pittsburgh, and served in the same position at Lehigh University from 1930 through 1936, at which time he became Assistant Professor of Physics and served in that position until 1940. He was a Guggenheim Fellow in the seismic investigation of oceans basins from 1938 to 1940, when he returned to Lehigh University where he held the position of Associate Professor of Geology until 1944. From 1944 to 1947 he was Associate Professor of Geology at Columbia University. Since 1940 Dr. Ewing has been a Research Associate at Woods Hole Oceanographic Institute. Since 1947 he has been Professor of Geology at Columbia University, and since 1949 Director of Lamont Geological Observatory. Dr. Ewing has been a member of the panel of the Research & Development Board, and since 1950 has been Associate in Geophysics at Woods Hole Oceanographic Institution.

Dr. Ewing received an honorary Sc.D. at Washington & Lee University in 1949. During the same year he became Arthur L. Day Medalist of the Geological Society of America and was Joseph Henry Lecturer. In 1951 he was Westbrook Lecturer, and was Distinguished Lecturer of the AAPG in 1947 and 1953. Also in 1953 he was Distinguished Lecturer for SEG.

Dr. Ewing's scientific discoveries include seismic reflection and refraction in ocean basins, ocean bottom photography, the Bathythermograph, SOFAR sound transmission, and deep-sea coring. He is a member of American Physical Society, American Mathematical Society, Geological Society of America, Seismological Society of America, American Geophysical Union, New York Academy of Sciences, American Association for the Advancement of Science, American Geographical Society, Bermuda Biological Association, Phi Beta Kappa, the Society of the Sigma Xi, National Academy of Sciences, Society of Exploration Geophysicists, National Geographic Society, American Association of Petroleum Geologists, and American Academy of Arts and Sciences.

BRUCE C. HEEZEN

BRUCE C. HEEZEN, a native of Iowa, received his B.A. in geology from The State University of Iowa in 1948. Between 1948 and 1951 he was Roberts Fellow at Columbia University, studying geology and conducting research in submarine geology and submarine geophysics. In the spring of 1952 he completed requirements for the M.A. and in the spring of 1954 passed the Ph.D. examinations in geology at Columbia University. Since the summer of 1947 he has been active in marine research, first at the Woods Hole Oceanographic Institution and later at Columbia University. From its beginning in 1949 he has been on the staff of the Lamont Geological Observatory, first as research assistant and later as research associate. A member of over a dozen deep sea expeditions, he has been chief scientist of six expeditions in the north and south Atlantic. He has written on the results of deep sea exploration and on related problems of topography and sedimentation.

Professional affiliations include the Society of Exploration Geophysicists, American Geophysical Union, American Association of Petroleum Geologists, American Association for the Advancement of Science, and the Society of the Sigma Xi.

HAINES C. HIBBARD

HAINES C. HIBBARD received a B.S. Degree in Engineering Physics from the University of Tulsa in 1949.

Mr. Hibbard was with the Shell Oil Company just prior to World War II. He spent the war years as an Air Force Radar Officer. Since 1946 he has been employed as a research engineer by The Carter Oil Company at their Tulsa laboratory.

Mr. Hibbard is an associate member of IRE and a member of the Geophysical Society of Tulsa.

BENJAMIN F. HOWELL, JR.

BENJAMIN F. HOWELL, JR., was born in Princeton, N. J. in 1917. He prepared for college at the Lawrenceville School, graduating in 1935. He attended Princeton University where he received his A.B. degree in 1939 with a major in geology. While a student he worked during summers for four years on the Geological Survey of Newfoundland, and from 1939 to 1942 he attended the California Institute of Technology, with a major in geophysics, getting his Master of Science degree in 1942. For the following two years he worked as a research engineer in the University of California, Division of War Research Laboratory, at San Diego, California. In 1945 he joined the research laboratory staff of United Geophysical Company in Pasadena, where he worked on instrumentation problems. In 1947 he returned part time to the California Institute of Technology, while he continued to work for United, receiving his Ph.D. degree in 1949. Since 1949 he has been in charge of the geophysics program at the Pennsylvania State University, where he is currently Professor of Geophysics and Head of the Department of Geophysics and Geochemistry. He is a member of the Society of Exploration Geophysicists, the Seismological Society of America, the American Geophysical Union, the Geological Society of America, the Pennsylvania Academy of Science, and the Society of Sigma Xi. He is Secretary of the Eastern Section of the Seismological Society of America. He is Chairman of the Committee on Fundamental Geophysical Research on the National Science Foundation.

FRANKLYN K. LEVIN

FRANKLYN K. LEVIN received a B.S. degree from Purdue University in 1943 and a Ph.D. degree in physics in 1949 from the University of Wisconsin.

During World War II, Dr. Levin worked on the Manhattan Project at the S. A. M. Laboratories. Since 1949, he has been employed as a research physicist by The Carter Oil Company at their laboratory in Tulsa. During 1953–1954, he was on leave of absence as assistant director of the Hudson Laboratories of Columbia University.

Dr. Levin is a member of the American Physical Society and Society of the Sigma Xi.

KATURO MAEDA

KATURO MAEDA was graduated from the Faculty of Science, University of Kyoto in 1941, and filled a post in the Central Aeronautical Research Institute of Japan, studying aeronautics there until 1945. Since 1946 he has been a research engineer on the staff of the Railway Technical Research Institute, Japanese National Railways, working in the field of applied mathematics. His theoretical research in geophysics began in 1948, and has included work on simplification of Slichter and Pekeris' method of interpretation of apparent resistivity curves obtained by electrical drilling using orthogonal and normal functions, mathematical interpretation of apparent resistivity curves in the case of electrical trenching, and the dipping-bed problem. On the basis of these studies he received a Doctor of Engineering degree from Kyoto University in 1952.

Dr. Maeda has been a member of the Society of Exploration Geophysicists of Japan since 1950, and since 1952 has served on its Committee.

ROBERT B. RICE

ROBERT B. RICE received the B.A. degree in mathematics and physics from the College of Wooster, Wooster, Ohio, in 1941. He joined Phillips Petroleum Company in the summer of 1941 as a reservoir engineer in the Production Department. From 1941 to 1945 he taught and did graduate work in the Department of Mathematics, Ohio State University. In 1945 he returned to Phillips as a process and design engineer in the Gasoline Department. Since 1946 he has worked in the Geophysical Section of the Research Division, in which he is now a group leader.

Mr. Rice is a member of the American Mathematical Society, the Mathematical Association of America, the American Institute of Physics, the Geophysical Society of Tulsa, the Society of Exploration Geophysicists, and the European Association of Exploration Geophysicists.

EMMET D. RIGGS attended Arlington State College, the University of Texas, and Southern Methodist University and received a B.A. degree in physics from Texas and an M.S. degree in electrical engineering from S.M.U.

He was employed by The Atlantic Refining Company on various geophysical field parties during summer vacations beginning in 1934. He served five years as an officer in the Signal Corps (1940–1945) and at the conclusion of the war returned to Atlantic as a seismic observer. This was followed by a transfer in 1946 to the Geophysical Laboratory of the company at Dallas as an electrical engineer.

He is a member of the Society of Exploration Geophysicists, the American Geophysical Union, and the Dallas Geophysical Society, and is an associate of the Acoustical Society of America. He is also registered as a professional engineer by the Texas State Board of Registration for engineers.

EMMET D. RIGGS

Biographies and photographs of other authors of papers in this issue have appeared in recent issues of GEOPHYSICS as follows: KENNETH L. COOK and C. HEWITT DIX, v. XIX, p. 844 (October, 1954); ROBERT G. VAN NOSTRAND, v. XIX, p. 848 (October, 1954); and J. L. WORZEL, v. XIII, p. 490 (July, 1948).

REPORTS OF MEETINGS

EIGHTH ANNUAL MIDWESTERN MEETING

HOTEL ADOLPHUS, DALLAS, TEXAS
NOVEMBER 18–19, 1954

TECHICAL SESSIONS

Welcoming Address

C. G. DAHM, Hunt Oil Company, Dallas, Texas

Presidential Remarks

PAUL L. LYONS, Anchor Petroleum Company, Tulsa, Oklahoma

Geophysics in an Expanding Economy

JAMES BOYD, Kennecott Copper Company, New York, N. Y.

Notes on the Geograph

W. W. NEWTON, Delhi Oil Corporation, Dallas, Texas

A New Seismic Technique

BURTON MCCOLLUM, McCollum Exploration Company, Houston, Texas

A technique comprising utilization of seismic energy from a large weight dropping at closely spaced intervals, correcting the time of reflected events for stepout and elevation, and integrating the corrected individual seismogram to give a composite seismogram that attenuates the horizontal and low angle event and accentuating the time corrected reflected event.

Specific Combinations of Multiple Charges with Multiple Detectors Improve Attenuation of Disturbances

J. O. PARR, JR., and W. H. MAYNE, Petty Geophysical Engineering Co., San Antonio, Texas

Multiple units (either charges or detectors) with a gradation of the effectiveness attenuate a continuous band of disturbing wavelengths better than multiple units with uniform effectiveness. Good attenuation can be obtained from combinations of multiple charges with multiple detectors which have (1) concurrent, (2) complementary, or (3) overlapping attenuation bands. These are obtained by (a) use of a different arrangement or number of the charges from that of the detectors, (b) a specific gradation of the effectiveness of the units, or (c) spacing of the charges with a definite ratio to the spacing of the detectors for the particular pattern used.

Seismogram Synthesis from Velocity Data

R. A. PETERSON, United Geophysical Corporation, Pasadena, California

The availability of continuous velocity data provides a closer insight into the seismic reflection process in layered rocks. Methods are described for the synthesis of seismograms from these data, and illustrations are given of field results.

The Reynolds Plotter

VINING T. REYNOLDS, Geophysicist, Houston, Texas, and PAUL FARREN, National Geophysical Company, Houston, Texas

A system of seismic trace analysis is presented which mechanically identifies, times, corrects, computes, and plots in cross section form every event on a seismic record. Normal moveout, weathering corrections, elevation corrections, and velocity depth functions are applied to each trace individually as all traces are scanned and reproduced simultaneously by a mechanical process.

Benefits of the system might be listed from two viewpoints. First, as a plotter, the system produces cross sections plotted with speed, thoroughness and accuracy. Second, as an interpretational

tool, the system by the speed and convenience in correlation of the seismic sections, expands the output of the interpreter; by flexibility in handling the mass of data available, it facilitates special projects such as velocity and isopach studies; and by thoroughness of presentation of all events, especially segmental reflections, it permits a more valid interpretation.

A General Low Frequency Electrical Earth Model

WILLIAM C. PRITCHETT, The Atlantic Refining Co., Dallas, Texas

A general earth model is described which simulates the earth when excited by currents either conductively coupled to the earth by electrodes or inductively coupled to the earth by loops. Consideration of model equations showed that a material with a resistivity of approximately 10^{-4} ohm-meters was desired for use in the model. Although suitable materials with this resistivity were not known, it was found that fine bronze wheel grindings held together by wax did have the required macroscopic resistivity. Using this model, surface measurements revealed only minor anomalies resulting from a simulated salt dome three-quarters of a mile in diameter, one-half mile below the surface.

Discussion: ROBERT VAN NOSTRAND, Magnolia Petroleum Company, Dallas, Texas

*Magnetic Exploration by MoMag**

W. T. GRISWOLD, United Geophysical Corporation, Pasadena, California

The introduction of the automatic recording total intensity mobile magnetometer has greatly increased the rate at which certain types of magnetic surveying may be carried out. This unit, known as The MoMag, is mounted on a heavy duty 4-wheel drive vehicle and is suitable for operation under a wide range of field conditions. However, greatest efficiency is obtained in operations along roads. Under suitable conditions, surveys can be made at speeds as high as 40 miles per hour and the cost per survey mile is lower than any other magnetic surveying method.

MoMag surveys have been particularly valuable in locating and outlining mineralization associated with magnetite deposits. Due to the frequent occurrence of magnetite as an associate mineral in high temperature fissure veins and contact replacement deposits, ore minerals of such metals as copper, lead, zinc, tungsten, and molybdenum may be found. The unit is also valuable for delineating fault zones, basement highs and lows, intrusive sedimentary contacts, sub outcrops of basic dikes or bedded volcanics, buried volcanic flows, regional dips and strikes and hydrothermal alternation zones.

* Trademark, United Geophysical Corporation.

The Use of the Magnetic Method in Searching for Stratigraphic Traps

JOHN D. HASEMAN, Linton, Indiana

A procedure is described by which very accurate corrections can be made for the local effects of regional maximum and minimum vertical magnetic intensities, thereby permitting a closer correlation between magnetic anomalies and geologic structure.

It is postulated that variations in the circulation of earth currents resulting from geochemical differences associated with dry and oil bearing horizons produces a measurable change in the magnetic vertical intensity which can be used in prospecting.

Some examples are presented which indicate that under certain conditions the value of vertical magnetic intensity might vary at a particular point, but the pattern of magnetic intensity remains the same.

Discussion: WILLIAM M. BARRET, William M. Barret, Inc., Shreveport, La.

A Personnel Training and Development Program for Geophysicists

H. R. PRESCOTT, Continental Oil Co., Houston, Texas

Geophysics is a young profession created by people attracted from numerous allied fields in

engineering, geology, physics and mathematics. The development of these people into mature geophysicists has largely been an informal process. There appear to be some advantages in a more formal approach to personnel training and development in the industry in order to supply future needs.

Discussion: CECIL H. GREEN, Geophysical Service Inc., Dallas, Texas

Cars, Trucks, and Doodlebuggers

R. FITZPATRICK, Transportation Consultant, Houston, Texas

A discussion of the highway hazards encountered in geophysical operations, and of the problem of preventive maintenance. The value of driver selection and training is strongly emphasized.

Safe Handling and Use of Explosives in Seismic Operations

LINDLEY LATHUM and NORMAN G. JOHNSON, E. I. duPont de Nemours and Co., Wilmington, Delaware

Explosives can be used safely if fundamental regulatory precautions are established, explained, and enforced. A discussion of suggested safe practices and comments on hazards in the use of explosives on conventional, pattern, offshore, and experimental operations. Safe storage, transportation, and handling of explosives and shot point and shot boat procedures will be described.

Atmospheric Electricity and Geophysical Operations

GLENN W. FORDHAM, The Atlantic Refining Co., Dallas, Texas

Lightning has caused occasional loss of life directly by a strike and indirectly by a premature detonation of dynamite. Corona currents resulting from high potential gradients in the atmosphere have been measured using a point collector, in the hope that a simple device giving some degree of prior warning of imminent flash can be developed. Continuous recordings have been taken of corona currents during thunder, snow, and rain storms.

Hazards of Static in the Use of Electric Blasting Caps in Seismic Operations

G. M. KINTZ, H. F. BROWNE, and P. M. HANAHEN, U. S. Bureau of Mines

A demonstration and discussion of the hazards of static electricity in the course of seismic operations. Precautionary measures are demonstrated.

Geology of Uranium on the Colorado Plateau

HOBART STOCKING, U. S. Atomic Energy Commission, Grand Junction, Colorado

The U. S. Geological Survey's Development of Instruments and Techniques for Measuring Radioactivity in the Field

FRANK STEAD, U. S. Geological Survey, Denver, Colorado

The principal emphasis of the U. S. Geological Survey's investigations in the field of radioactivity has been placed on the development of instruments and techniques and rapid field measurement of radioactivity. Some current activities include the development of portable radiation-detection equipment, gamma ray logging of exploratory drill holes, original-state core studies, and air-borne radioactivity surveying. Significant progress has been made in instrumentation and techniques; however, considerable research must be done to place field measurements of radioactivity on a quantitative basis.

Exploration and Production at the Mi Vida Mine

CHARLIE STEEN, Utex Exploration Company, Moab, Utah

Problems in Detection of Seismic Signals

HAL J. JONES, Texas Instruments Incorporated, Dallas, Texas

The problem of detection and extraction of signals in noise backgrounds has received considerable study in modern communications theory and information theory. Emphasis has been upon statistical treatment in an attempt to take advantage of randomness of background noise. This paper presents a discussion of several criteria which have been applied in the design of recording systems to enhance signal discrimination. Specific equipment for some optimized linear filters is described. Possible applicability of these criteria to seismic reflection recording problems is discussed. The nature of typical seismic signals and background noise is outlined as a means of specifying criteria which can be applied to the problem of designing an optimum detection filter for seismic reflection signals. The possible use of non-linear decision-making filters in seismic recording systems is discussed both from the standpoint of theory and of suitable equipment.

Trends in Seismic Amplifier Development

A. E. TILLEY, California Research Corporation, La Habra, California

The petroleum industry is rapidly integrating reproducible recording techniques into its routine operations. In general, the quest is for better data from areas of poor records and from operations under severe environmental conditions. Whether these operations be with conventional instrumentation or with magnetic recording, we find that more attention is being devoted to the seismic amplifier characteristics. Instrument performance characteristics, such as dynamic range, nonlinear distortion, noise, and reliability are being specified and related to the problem. Performance criteria can be established to help guide instrument development and thereby insure that these needs of industry are met.

The present state of the art makes possible amplifier sensitivity of better than one microvolt with noise below one-tenth of a microvolt. Pre-filter nonlinear distortion should be as low as one-tenth of one per cent under many normal operational conditions.

Through cooperative effort among seismic instrument manufacturers, contractors, and clients, we can obtain better geophysical data through instrument improvement.

Some Recent Transistor Developments—The Silicon Transistor

G. K. TEAL, Texas Instruments Incorporated, Dallas, Texas

In this discussion of transistor electronics a description will be given of some recent developments in materials, techniques, and designs that have contributed to the availability of a variety of transistors and diodes. These devices are well suited to the solution of many problems of circuitry and instrumentation. Of particular interest are new silicon devices which are produced only by Texas Instruments. Silicon transistors have been made by a process sufficiently reproducible that production units have been available for some time. These transistors show superior characteristics with respect to high temperature operation and to power handling capabilities. The possibilities of applying transistors to geophysical equipment will be briefly discussed.

Seismic Recorder for Monitoring Magnetic Tape

GEORGE B. LOPER, Magnolia Petroleum Co., Dallas, Texas

A seismic recorder utilizing Polaroid "picture-in-a-minute" film is used during recording of seismic data on magnetic tape. Signals from 12 magnetic recording heads are applied through appropriate networks to conventional galvanometers in the monitor camera. The optical system is arranged to make a miniature seismogram of conventional appearance which is produced on the standard 3×4 inch Polaroid print. The record is a satisfactory guide for the operator to evaluate the quality of the record on the magnetic tape without the need for playing it back.

Simultaneous Gamma Ray and Resistivity Logging as Applied to Uranium Exploration

R. A. Broding and Ben F. Rummerfield, Century Geophysical Corporation, Tulsa, Okla.

The transferring of petroleum exploration thinking and methods to uranium exploration has greatly facilitated the search for radioactive ores. The application of radioactive and resistivity logging to locate mineralized zones in shallow core holes obviates the need and expense of taking continuous cores. Instrumentation, field equipment, and techniques are discussed.

Field Measurements of Reflection and Surface Wave Amplitudes

E. D. Riggs, The Atlantic Refining Company, Dallas, Texas

A series of field measurements of reflection and surface wave amplitudes has been made from routine seismic shots in various areas. The effect of variation of charge size on both events is illustrated.

Refraction Seismograph Techniques in South Florida

Alex E. Blomerth, Gulf Oil Corporation, Ft. Myers, Florida

This paper deals with the operational techniques of a refraction seismograph party in South Florida using two recording units. A brief discussion is made concerning the general geology and topography of the area. Procedures and problems of the recording, surveying and permitting, drilling, transportation, and communications are presented. A short dissertation is made concerning velocities and interpretation.

A Study of Gravity Response within Certain Gravity Provinces of Texas, Louisiana, and Mississippi

Clark Mayhew, Union Producing Co., Shreveport, Louisiana

The efficiency of an oil and gas exploration program often can be improved by the use of gravity surveys. The amount of improvement varies with areas and because of its empirical nature is difficult to determine. However, the importance of knowing the probable value of gravity coverage in a given area justifies even an approximate analysis of the situation.

From the region of Texas, Louisiana, and Mississippi, we have outlined six areas containing Bouguer gravity anomaly prospects of similar character, designating these as "gravity provinces." For each such province, there is described a statistical analysis of gravity response over known oil and gas fields. A probability ratio computed for each province shows the relative value of gravity work as a reconnaissance method.

Making Use of Seismic Record Morgues

H. B. Peacock, Geophysical Consultant, Dallas, Texas

The original cost of seismic records in storage vaults is estimated and an attempt is made to place a present-day evaluation on them. The extent to which old records are being used and the methods applied are discussed. Some factors limiting the usefulness of these records are pointed out and suggestions are made for correcting the deficiencies. The effect of magnetic tape recording on the storage problem is mentioned. Mention is also made of the recently organized "Record Bank" for the purpose of trading seismic records on an exchange basis.

Exploration History of the Block 12 Area, Andrews County, Texas

J. H. Deming and L. O. Dailey, Jr., The Atlantic Refining Co., Dallas, Texas

The authors review the general history of the Block 12 area, Andrews County, Texas, from the first geologic interest in the area in 1920 to the present time. Successive torsion balance, gravimetric, and seismic mapping are presented and discussed. Subsurface geologic mapping and a geologic cross-section based upon well control are also presented with a summary of the generalized stratigraphy.

The authors call attention to a seeming correlation between progressive changes in reflection character and truncation of geologic markers.

The Geophysical History of the Elkhorn Field, Crockett County, Texas

J. E. FINLEY, Continental Oil Co., Midland, Texas

This paper reviews the refraction and reflection geophysical surveys employed in the exploration and development of the Elkhorn Field. Map interpretations and cross-sections are presented and discussed. The results and limitations of both the reflection and refraction work are pointed out and actually compared to subsurface conditions.

Case History of the Elk City Field

R. F. CHRISTY, Shell Oil Company, Tulsa, Oklahoma

The Elk City Field is in T10N, Rs. 20, 21, 22 W., Beckham County, Oklahoma. The history of the geophysical exploration leading to the discovery is presented.

The Shell Oil Company entered the area in 1945 after seismic work had been done by several other companies. A dry hole, the deepest well in Oklahoma at that time, had been drilled on the structure in 1940. The presentation of data includes seismic records, profiles, and maps on two horizons as well as an up-to-date subsurface map.

Case History of the Smallwood Pool, Stafford County, Kansas

B. W. BEEBE and A. L. BALLOU, JR., Manhart, Millison and Beebe, Tulsa, Okla.

The Smallwood pool was discovered in August, 1951, as a result of a seismic survey conducted in a manner in which the geological and geophysical data were completely coordinated throughout the extent of the survey. This discovery is unusual in that prior to 1951 numerous operators conducted seismic surveys which apparently overlooked the pool in an area of excellent seismic reflection data that are very accurate if proper interpretation techniques are applied.

The scope of this paper is to outline the seismic and geologic problems and to discuss the techniques used in exploring and evaluating the Smallwood and other similar areas where structural relief is very low and a high degree of seismic accuracy is required.

The Devonian Problem

JOHN DALY, Consulting Geologist and Geophysicist, Midland, Texas

A generation of geophysicists has been weaned on the continuous profiling method which, for the purpose of mapping the Devonian formation, is not completely salutary, since this formation is severely faulted and reflections from it are not consistently continuous. There is a tendency to force continuity where none exists. The principles for mapping the Devonian formation, enunciated herein, can be applied equally well to the mapping of any faulted strata.

The first step is the identification of the reflection, which is achieved by means of velocity surveys and allowance must be made for the lag in time of the reflected event.

The second step is to discern when a fault is crossed and the third is to recognize the same event after this has occurred. Good records facilitate accomplishing the second and reflection character is a requisite for solving the third problem.

The Geology of the Cambrian Trend of West Central Texas

FRANK B. CONSELMAN, Consulting Geologist, Abilene, Texas

The outstanding recent exploratory activity in West Central Texas has been the search for Cambrian oil, particularly in Coke and Nolan Counties. The Cambrian Trend consists of a series of fields now extending from White Flat on the north to Bronte on the south, aligned along the truncated crest of a narrow ridge on the upthrown western side of the Fort Chadbourne fault trend. The

Fort Chadbourne fault system includes local deeply depressed graben areas, extending parallel to or southwestward from the main high-angle fault. The greater part of the movement was early Pennsylvanian, and probably related to the Ouachita orogeny, with subsequent movements during Strawn and Canyon time possibly continuing into post-Permian time.

The principal Cambrian oil-producing formation is the Wilberns, including both sandy and limy facies. All known Cambrian oil appears to have been derived from younger sources, particularly the Pennsylvanian.

The magnitude of the faulting involved in the Cambrian trend presents an interesting geophysical challenge in recognizing seismic, gravitational, and magnetic anomalies associated with this structure. Extension of the trend to the north and south, or the discovery of similar fault systems paralleling the present trend, should provide an incentive for continued exploration in the area.

EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS

SEVENTH MEETING

HAAGSCHE DIERENTUIN, THE HAGUE, NETHERLANDS

DECEMBER 8–10, 1954

TECHNICAL SESSIONS

Gravity Variations in Surveys across Geological Boundaries.

G. C. COLLEY

"Schweydar" Formulae for the Topographic Reduction of Gravity.

K. JUNG

Discussions on Safety.

Détermination des salinités des eaux à grandes profondeurs dans le sous-sol du Zuiderzee par prospection géophysique.

A. VOLKER & E. O. HOUTSMA

Resistivity Curves for a Conductive Layer of Finite Thickness embedded in an otherwise Homogeneous and less Conductive Earth.

O. KOEFOED

Étude théorique de la vitesse des ondes de compression dans les vases.

Y. D'ERCEVILLE

Theoretical Considerations Concerning a Selection of Frequencies Caused by the Reflection of Seismic Pulses.

J. BAUMGARTE, H. MENZEL, AND O. ROSENBACH

Eine tragbare geophysikalische Werkstatt.

I. LUCIC

The Behaviour of the Large Dykes from a Geophysical Point of View.

P. CALOI

A Low-Frequency Refraction Geophone.

W. M. JONES & A. T. DENNISON

Mesure du bruit et sismos multiples: étude expérimentale dans les landes.

R. RICHARD & M. RIMBAUT

Travel-Time Curves of Normal Rays in Reflexion Seismics.

W. BRAUCH

Gravity Map of Europe.
J. W. DE BRUYN

Relative Determination of the Density of Surface Rocks and the Mean Density of the Earth from Vertical Gravity Measurements.
W. DOMZALSKI

Gravity Surveying in the East Carmarthenshire Anthracite Coalfield.
J. T. WHETTON, J. O. MEYERS and I. J. WATSON

Some Applications of Modern Well Logging Methods to Limestone Formations.
J. L. MATHIEU & C. ROSOFF

Depth Determination by means of Gravimetrical Sounding.
F. SUMI

Le complétement de l'exploration du soulèvement de Ferrara aved la méthode du gradient vertical.
C. MONNET

Theoretical Contemplations on the Reflexion of Seismic Waves in Siegerland Siderite Veins.
A. STEIN

Protractor for Quick Construction of Refracted Rays.
J. SCHOEFFLER & E. DIEMER

Reflexion Survey in Rough Topography.
A. M. SELEM

Recent Research on Palaemagnetism and some Possible Applications to Geological Problems.
S. K. RUNCORN

Abaques "Verticaux" pour le calcul et l'interprétation des anomalies magnétiques: exemples d'application.
V. BARANOV

Remarks on the Establishment of a European Map of the Z-Anomalies.
H. CLOSS

Statistical Methods in Geophysical Prospecting.
M. MATSCHINSKI

GEOPHYSICAL CONFERENCE IN SOUTH AFRICA

A successful conference on geophysical subjects was held at the University of the Witwatersrand, Johannesburg, from July 19 to July 22, under the auspices of the Bernard Price Institute of Geophysical Research. The field covered: recent determinations of the ages of rocks and their geological implications (8 papers), geodesy (4 papers), crustal structure of the earth including seismological and gravity investigations (11 papers), geomagnetism (4 papers), the mechanical properties of rocks including the phenomena of rock bursts (5 papers), the earth's heat and its origins (5 papers), the interior of the earth (4 papers) and geophysical prospecting (4 papers). Between 50 and 100 scientists and interested persons from South Africa attended and showed interest in all the aspects of geophysics mentioned. Visitors whose presence contributed materially to the success of the conference were Dr. Francis Birch of Harvard University, Dr. Robert Stoneley of the University of Cambridge, and Dr. C. J. Jaeger of the Australian National University, Canberra. Other visitors came from the neighbouring British protectorates and the Belgian Congo. Papers were received in addition from M. A. Tuve and H. E. Tatel of the Department of Terrestrial Magnetism, Washington, from Professor L. Cahen of the Musee Royal du Congo Belge, Tervuren, and from the National Meteorological Service of Portugal. The papers will be published by the authors independently in various scientific journals.

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Roy L. Lay — Curtis H. Johnson

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J. HARLAN JOHNSON	GERALD M. WESTBY*	RONALD E. MCADAMS
		H. E. STOMMEL*

DIRECTORS OF THE AMERICAN GEOLOGICAL INSTITUTE

CURTIS H. JOHNSON (Nov., 1956) SIGMUND HAMMER (Nov., 1955)

REPRESENTATIVE ON DIVISION OF EARTH SCIENCES
NATIONAL RESEARCH COUNCIL

C. B. BAZZONI (June, 1955)

REPRESENTATIVE ON COUNCIL OF
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

ROLAND F. BEERS, Beers and Heroy, Troy, N. Y.

* SEG Members.

LOCAL SECTIONS

GEOPHYSICAL SOCIETY OF TULSA

(CHARTERED FEBRUARY 2, 1948)

President: L. Y. FAUST, Amerada Petroleum Corp., Box 2040, Tulsa 2, Okla.
1st Vice-President: FRANK SEARCY, Continental Oil Co., Drawer 1267, Ponca City, Okla.
2nd Vice-President: BEN F. RUMMERFIELD, Century Geophysical Corp., Box 6216, Tulsa 17, Okla.
Secretary: T. S. GREEN, Sunray Oil Corp., Box 2039, Tulsa 3, Okla.
Treasurer: FIELDING L. MITCHELL, The Carter Oil Co., Box 801, Tulsa 2, Okla.
Editor: CHARLES W. OLIPHANT, Oliphant Laboratories, Inc., 1905 National Bank of Tulsa Bldg., Tulsa 3, Okla.
District Representatives:
A. B. BRYAN ('55), The Carter Oil Co., Box 801, Tulsa 2, Okla.
W. T. BORN ('56), Geophysical Research Corp., Box 2040, Tulsa 2, Okla.
NORMAN RICKER ('57), The Carter Oil Co., Box 801, Tulsa 2, Okla.
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, Room 224, Petroleum Science Hall.

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON SECTION

(CHARTERED FEBRUARY 14, 1948)

President: T. O. HALL, General Geophysical Co., 2514 Gulf Bldg., Houston 2, Texas
1st Vice-President: FRED E. ROMBERG, Geophysical Service Inc., 839 Esperson Bldg., Houston 2, Texas
2nd Vice-President: A. A. HUNZICKER, Seismic Explorations, Inc., 1007 S. Shepherd, Houston, Texas
Secretary: H. W. MCDONNOLD, Keystone Exploration Co., 2813 Westheimer, Houston, Texas
Treasurer: W. B. LEE, Gulf Research & Development Co., Drawer 2100, Houston, Texas

District Representatives:
O. B. HOCKER, The Texas Co., Box 2332, Houston 1, Texas
G. A. BERG, Berg Geophysical Co., 2122 Welch, Houston, Texas
JOHN F. ANDERSON, Anderson & Cooke, 500 San Jacinto Bldg., Houston, Texas
Meetings: Monthly, 1st Monday, Noon luncheon ($1.50), Rice Hotel.

PACIFIC COAST SECTION

(CHARTERED APRIL 12, 1948)

President: JOHN W. MATHEWS, Richfield Oil Co., Box 147, Bakersfield, Calif.
Vice-President Northern District: RICHARD W. SHOEMAKER, Ohio Oil Co., Box 193, Bakersfield, Calif.
Vice-President Southern District: ELLSWORTH M. CULRY, Shell Oil Co., 1008 W. 6th St., Los Angeles 17, Calif.
Secretary-Treasurer: L. I. BROCKWAY, Western Gulf Oil Co., Box 1392, Bakersfield, Calif.
District Representatives:
FLINT H. AGEE, United Geophysical Corp., 2227 S. 4th Ave., Arcadia, Calif.
WM. D. CORTRIGHT, Tide Water Associated Oil Co., 2202 Terrace Way, Bakersfield, Calif.
MILTON C. BORN, Amerada Petroleum Corp., 552 Subway Terminal Bldg., Los Angeles, Calif.
Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles.

DALLAS GEOPHYSICAL SOCIETY

(CHARTERED AUGUST 7, 1948)

President: R. C. DUNLAP, JR., Geophysical Service Inc., 5900 Lemmon Ave., Dallas 9, Texas
1st Vice-President: MARTIN C. KELSEY, Rayflex Exploration Co., 6923 Snider Plaza, Dallas, Texas
2nd Vice-President: TOM PRICKETT, The Atlantic Refining Co., Box 2819, Dallas 1, Texas
Secretary-Treasurer: JOHN T. GEER, Magnolia Petroleum Co., Box 900, Dallas 1, Texas
District Representatives:
O. C. CLIFFORD, JR., The Atlantic Refining Co., Box 2819, Dallas 1, Texas
CECIL H. GREEN, Geophysical Service Inc., 5900 Lemmon Ave., Dallas 9, Texas
J. P. WOODS, The Atlantic Refining Co., Box 2819, Dallas 1, Texas
Meetings: Monthly, generally but not invariably 2nd Monday (contact any member). 8:00 P.M. Fondren Science Bldg., S.M.U.

FORT WORTH GEOPHYSICAL SOCIETY

(CHARTERED AUGUST 7, 1948)

President: E. J. GEMMILL, Cities Service Oil Co., 1111 Ft. Worth National Bank Bldg., Fort Worth, Texas
Vice-President: H. E. PROKESH, Continental Oil Co., 1710 Fair Bldg., Fort Worth, Texas
Secretary-Treasurer: JAMES DIVELBISS, The Chicago Corp., 2111 Continental Life Bldg., Fort Worth, Texas
District Representative: R. W. DUDLEY, Kerr-Dudley & Co., 1623 Oil & Gas Bldg., Fort Worth, Texas
Alternate District Representative: FRANK O. MORTLOCK, Gulf Oil Corp., Box 1290, Fort Worth, Texas
Meetings: Monthly, 4th Monday, Noon luncheon ($1.50), Texas Hotel.

ARK-LA-TEX GEOPHYSICAL SOCIETY

(CHARTERED MARCH 12, 1949)

President: J. RYAN WALKER, Arkansas Fuel Oil Corp., Box 1117, Shreveport, La.
Vice-President: GLENN J. BAKER, Wm. M. Barret, Inc., 1431 Dalzell, Shreveport, La.
Secretary-Treasurer: BRUCE FOX, The Atlantic Refining Co., 922 Texas Eastern Bldg., Shreveport, La.

District Representatives:
B. B. BURROUGHS, Sunray Oil Corp., Ricou-Brewster Bldg., Shreveport, La.
ROBERT B. BAUM, Seismograph Service Corp., 607 Shelby Bldg., Shreveport, La.
Meetings: Monthly, last Monday, Noon luncheon ($1.50), Caddo Hotel, Shreveport.

PERMIAN BASIN GEOPHYSICAL SOCIETY

(CHARTERED JANUARY 30, 1950)

President: J. E. FINLEY, Continental Oil Co., Box 431, Midland, Texas
1st Vice-President: J. S. PLUTA, Honolulu Oil Corp., Drawer 1391, Midland, Texas
2nd Vice-President: R. M. PINSON, Union Oil Co., 619 West Texas, Midland, Texas
Secretary: BILLY C. JOHNSON, Forest Oil Corp., Box 2066, Midland, Texas
Treasurer: N. R. PARK, Standard Oil Co. of Texas, McClintic Bldg., Midland, Texas
District Representative: PAUL C. REED, Forest Oil Corp., Box 2066, Midland, Texas
Meetings: Monthly, 2nd Tuesday, 7:30 P.M., free coffee and doughnuts, Cowden Jr. High School cafeteria.

DENVER GEOPHYSICAL SOCIETY

(CHARTERED MAY 19, 1950)

President: C. K. SHEPHERD, Continental Oil Co., Continental Oil Bldg., Denver, Colorado
Vice-President: E. B. WASSON, The California Co., Box 780, Denver, Colorado
Secretary-Treasurer: J. R. REEVES, Aurora Gasoline Co., 227 U. S. National Bank Bldg., Denver, Colorado
District Representative: DART WANTLAND, 727 Pearl St., Denver, Colorado
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only, Petroleum Club, 1644 Glenarm Place.

CANADIAN SOCIETY OF EXPLORATION GEOPHYSICISTS

(CHARTERED JANUARY 24, 1952)

President: W. P. OGILVIE, Accurate Geophysical Ltd., 1023 11th Ave. West, Calgary, Alberta
Vice-President: W. BAILIE, Frontier Geophysical Ltd., 1504 14th St. West, Calgary, Alberta
Secretary-Treasurer: H. COX, Western Geophysical Co. of Canada, Ltd., 828 4th Ave. West, Calgary, Alberta
District Representative: H. M. HOUGHTON, The Geophysical Prospecting Co. Canada Ltd., 411 6th Ave. West, Calgary, Alberta
Meetings: (Data not received)

GEOPHYSICAL SOCIETY OF OKLAHOMA CITY

(CHARTERED SEPTEMBER 30, 1952)

President: FRANK A. ROBERTS, The Carter Oil Co., 1411 Classen Blvd., Oklahoma City, Okla.
1st Vice-President: ARNOLD BLEYBERG, Consultant, 2416 Barclay Rd., Oklahoma City, Okla.
2nd Vice-President: J. EUGENE STONES, The Superior Oil Co., 2211 Liberty Bank Bldg., Oklahoma City, Okla.
Secretary: JOHN COCHRANE, Inland Seismograph Co., 508 NE 26th St., Oklahoma City, Okla.
Treasurer: CHARLES E. BECK, Stanolind Oil & Gas Co., Box 1654, Oklahoma City, Okla.
District Representative: D. W. RATLIFF, Stanolind Oil & Gas Co., Box 1654, Oklahoma City, Okla.
Alternate District Representative: R. D. ROBERTS, Sohio Petroleum Co., Box 3656, Oklahoma City, Okla.
Meetings: Monthly, 2nd or 3rd Monday, 6:30 P.M., Dinner ($1.53), Y.M.C.A., or Y.W.C.A.

CASPER GEOPHYSICAL SOCIETY

(CHARTERED MAY 23, 1953)

President: WENDELL H. HAWKES, Stanolind Oil & Gas Co., Box 40, Casper, Wyoming
Vice-President: T. L. MCCORKLE
Secretary-Treasurer: J. E. BROOKSHIRE, Box 720, Casper, Wyoming
District Representative: DON B. WINFREY, Winfrey Exploration Co., Box 755, Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., Dinner ($2.75), Townsend Hotel.

GEOPHYSICAL SOCIETY OF SOUTH TEXAS

(CHARTERED NOVEMBER 9, 1953)

President: JOHN C. COOK, Southwest Research Institute, 8500 Culebra Road, San Antonio 6, Texas
Vice-President: WELDON L. CRAWFORD, Petty Geophysical Engineering Co., Box 2061, San Antonio, Texas
Secretary-Treasurer: LAWTON B. STEPHENSON, Petty Geophysical Engineering Co., Box 2061, San Antonio, Texas
District Representative: BART PRATT, Petty Geophysical Engineering Co., Box 2061, San Antonio, Texas
Meetings: Semi-monthly, 2nd and 4th Wednesdays, Noon luncheon (Cafeteria style), Sommers Cafeteria, Main Plaza, San Antonio.

SOUTHEASTERN GEOPHYSICAL SOCIETY

(CHARTERED APRIL 1, 1954)

President: E. H. SHANNON, The Texas Co., 1501 Canal St., New Orleans, La.
Vice-President: D. D. UTTERBACK, Freeport Sulphur Co., American Bank Bldg., New Orleans, La.
Secretary-Treasurer: MERRILL SMITH, The Texas Co., Box 252, New Orleans, La.
District Representative: B. H. TREYBIG, JR., Louisiana Oil Exploration Co., Box 257, New Iberia, La.
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans.

DAKOTA GEOPHYSICAL SOCIETY

President: RALPH H. HOWE, The California Co., Box 1277, Bismarck, North Dakota
2nd Vice-President: WILLIAM HARLEY, Hercules Powder Co., 1000 14th St., Bismarck, North Dakota
Secretary-Treasurer: E. B. COLE, Cities Service Oil Co., Bismarck, North Dakota
District Representative: O. H. ARMSTRONG, Mobil Producing Co., Box 1236, Bismarck, North Dakota
Meetings: (Data not received)

MONTANA GEOPHYSICAL SOCIETY

(CHARTERED APRIL 12, 1954)

President: D. M. STEEL, Geotechnical Corp., 251 Avenue F, Billings, Montana
1st Vice-President: H. R. ADAMS, Sohio Petroleum Co., Box 529, Billings, Montana
2nd Vice-President: EDWIN BARTEL, Petty Geophysical Engg. Co., 403 North 24th St., Billings, Montana
Secretary-Treasurer: S. G. BUFORD, JR.
District Representative:
Meetings: (Data not received)

STUDENT SOCIETIES

(AFFILIATED)

COLORADO SCHOOL OF MINES SOCIETY OF STUDENT GEOPHYSICISTS

DEPARTMENT OF GEOPHYSICS
COLORADO SCHOOL OF MINES
GOLDEN, COLORADO

President: WILLIAM F. CLARKE
Vice-President: LEONARD ZASEYBIDA
Secretary-Treasurer: ROBERT MADDEN
Faculty Sponsor: JOHN C. HOLLISTER
Meetings: (Data not received)

GEOPHYSICAL SOCIETY OF SAINT LOUIS UNIVERSITY

President: CHARLES DALY, 4906 Argyle, St. Louis, Mo.
Vice-President: RICHARD SNEIDER, 3624 W. Pine, St. Louis, Mo.
Secretary: MICHAEL FORREST, 5529 Louisiana, St. Louis, Mo.

Treasurer: RONALD HAUG, 6950 Oleatha, St. Louis, Mo.
Faculty Moderator: REV. JAMES B. MACELWANE, S.J., Institute of Technology, 3621 Olive St., St. Louis 8, Mo.
Meetings: Monthly, 2nd Wednesday, 7:30 P.M., Meeting only, Institute of Technology, 3621 Olive Street.

HOUSTON STUDENT SECTION, SOCIETY OF EXPLORATION GEOPHYSICISTS

President: LEYCESTER STANLEY, 1804 Petroleum Bldg., Houston 2, Texas
1st Vice-President:
2nd Vice-President: J. L. WRIGHT, 1238 Harvard St., Houston 8, Texas
Secretary: R. D. LIBERDA, 914 Redwood, Apt. 2B, Houston 23, Texas
Treasurer: T. F. VINING, Bldg. 33, Apt. 3, University of Houston Village, Houston, Texas
University of Houston Sponsor: R. A. GEYER, 3743 Childress St., Houston, Texas
Rice Institute Sponsor: C. R. WISCHMEYER, 5321 Bordley St., Houston, Texas
Meetings: Monthly, last Friday, 7:30 P.M., alternately at the Library Auditorium, University of Houston, and the Physics Laboratory of the Rice Institute, meeting only.

UNIVERSITY OF TORONTO GEOPHYSICAL SOCIETY

DEPARTMENT OF PHYSICS
49 ST. GEORGE STREET
TORONTO 5, ONTARIO, CANADA

President: H. A. SHILLIBER
Vice-President: D. W. ALLAN
Secretary-Treasurer: R. D. RUSSELL
Faculty Sponsor: J. TUZO WILSON

Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George St.

UNIVERSITY OF TULSA STUDENT GEOPHYSICAL SOCIETY

DEPARTMENT OF GEOPHYSICS
THE UNIVERSITY OF TULSA
600 S. COLLEGE
TULSA 4, OKLAHOMA

President: KEITH CROUSE, JR.
Vice-President: R. M. CLINTON
Secretary: CECILE NASH
Treasurer: SCOTT SMITH
Faculty Sponsor: J. W. BERG

Meetings: Every Tuesday, 7:00 P.M., meeting only, Petroleum Science Hall.

NEW MEMBERS

ACTIVE

BRODINE, ROBERT V., *Geophysicist*, Gulf Research & Devel. Co., Box 2038, Pittsburgh 30, Pa.

BURNEY, WILLIAM M. JR., *Seismic Computer*, Humble Oil & Rfg. Co., Box 432, Palestine, Texas

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TRANSFER TO ACTIVE

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REINSTATEMENT

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KILBACK, N. R., *Party Chief*, Canadian Gulf Oil Co., Claresholm, Alta., Canada

KORNFELD, JOSEPH A., *Consultant*, 301 Oil Capital Bldg., Tulsa, Okla.

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KUHN, WILLIAM ALLEN, *Computer*, Marine Exploration Co., 7313 Burthe St., New Orleans, La.

LANGSTON, B. L., *Party Chief*, Western Geophysical Co. of Amer., 520 N. Market St., Shreveport, La.

LANGWELL, AUGUST III, *Gravity Computer*, Petty Geophysical Eng. Co., Drawer 2061, San Antonio 6, Texas

LAROCHELLE, ANDRE, *Technical Officer*, Geological Survey of Canada, National Museum, Ottawa, Canada

LEDBETTER, CHARLES E., *Computer*, Seismic Engineering Co., 2544 S. W. 29th St., Oklahoma City, Okla.

LOGAN, LEE W., *Gravity Engineer*, Humble Oil & Refg. Co., 202 Humble Bldg., Houston, Texas

MACDOUGALL, ROBERT E., 6549 Commodore Sloat Dr., Los Angeles 48, Calif.

MARDIROSIAN, AZAD, *Geophysical Trainee*, The Texas Co., Box 1356, Levelland, Texas

MARSHALL, IAIN, *Gravity Observer and Party Leader*, N. V. Nederlandsche Nieuw Guinee Petroleum Mij., Sorong, Netherlands New Guinea

MARSHALL, JOHN K., *Computer*, Seismograph Service Ltd., Holwood, Keston, Kent., England

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ROCKY MOUNTAIN SECTION REGIONAL MEETING

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

FEBRUARY 14–16, 1955
BILLINGS, MONTANA

"Milestones and Guideposts in Exploration" will be the theme of the 5th Annual Regional Convention of the Rocky Mountain Section of the American Association of Petroleum Geologists to be held in Billings, Montana, February 14–16, 1955. Host for this meeting will be the Billings Geological Society.

Technical papers on specific exploration and development programs will be presented by speakers from the industry in all member states of the Rocky Mountain section and Canada. The technical sessions will be held in the Fox Theater, two blocks north of the Northern Hotel, exhibition and registration headquarters for the convention.

ALASKA PETROLEUM RESERVE DATA TO BE MADE AVAILABLE BY NAVY

The Office of Naval Petroleum Reserves, Department of the Navy, has announced that all well records and geophysical data relating to oil explorations in Naval Petroleum Reserve No. 4, located in the vast sedimentary basin lying north of the Brooks Range in northern Alaska, would be available for public inspection and study beginning September 20, 1954 in the offices of the Geological Survey, Washington, D. C., Room 2643, Interior Building, and in the Office of the Inspector, Naval Petroleum Reserve No. 4, Fairbanks, Alaska.

This notice supplements that of the Department of the Interior on May 10, 1954, setting up open files in the above offices which made available for public inspection geologic reports, geologic maps, and similar technical data compiled by the Survey in connection with the Navy's exploration.

All of the area in northern Alaska north of the Brooks Range drainage divide was withdrawn from public entry by Public Land Order 82.

The task of publishing all information obtained by the Navy during the 10 years spent exploring for oil north of the Arctic Circle in Alaska has been undertaken by the Geological Survey. Initial publications describing some phases of the work are expected to be available in 1955.

The making available of additional technical data on the exploration at this time has been declared by the Navy to be in the public interest.

CALENDAR OF MEETINGS

Joint AAPG-SEPM-SEG Meeting, Hotel Statler, New York City, March 28–31, 1955
Permian Basin Geophysical Society Annual Meeting, Scharbauer Hotel, Midland, Texas, May 14, 1955
Tenth Annual Gulf Coast Meeting, San Antonio, Texas, May 19–20, 1955
Twenty-Fifth Annual Meeting, SEG, Shirley-Savoy Hotel, Denver, Colorado, October 3–6, 1955
Twenty-Sixth Annual Meeting, SEG, Roosevelt Hotel, New Orleans, La., October 29–31, November 1, 1956.
Twenty-Seventh Annual Meeting, SEG, The Conrad Hilton, Dallas, Texas, November 10–13, 1957.

JOINT MEETING OF THE AAPG-SEG-SEPM, NEW YORK, N. Y., MARCH 28–31, 1955

GENERAL ANNOUNCEMENT

The joint meeting of AAPG-SEG-SEPM will convene at the Hotel Statler, New York City, New York, March 28–31, 1955. The three professional societies represent the exploration branch of the petroleum industry and each will present three days of technical papers of interest to its membership.

The SEG technical sessions will begin in the Main Ballroom of the Hotel Statler at 9:00 A.M. Monday, March 28, and will move to the Georgian Room for the afternoon session. Papers of general interest will be presented at these two sessions for the benefit of all three societies' memberships.

Tuesday morning the three societies will meet together for the presidential addresses and honors and awards presentations.

The AAPG has arranged a field trip to Lamont Geological Observatory, where many interesting geophysical research problems are under study.

The Annual Dinner Dance is scheduled this year for Wednesday night and will feature the show from Broadway's famous Latin Quarter.

An extremely interesting program of technical papers is scheduled in an equally interesting location. The New York committees, under the general chairmanship of G. M. Knebel, have arranged for the first meeting on the East Coast to be a memorable one.

TENTATIVE TECHNICAL PROGRAM

MONDAY MORNING, MARCH 28, 1955

Papers of Interest to Geologists

1. Roy L. Lay, "Welcome"
2. Leo R. Newfarmer, "Present Day Frontiers of Oil Exploration"
3. Sigmund Hammer, "Geophysical Activity in 1954"
4. Fred J. Agnich and Clifford Flittie, "Seismic Exploration in Arabia"
5. H. P. Laubscher, "Structural and Seismic Deformations Along Faults in Eastern Venezuela"
6. Thomas J. O'Donnell, "Planning a Geophysical Program for an Unexplored Basin"
7. G. Lynn Shurbet, J. Lamar Worzel and Maurice Ewing, "Gravity Measurements at Sea, Part II Southern Part of East Coast of U. S."
8. J. Laurence Kulp and Wallace R. Broecker, "Recent Developments in C^{14} Dating"

MONDAY AFTERNOON, MARCH 28, 1955

Papers of Interest to Geologists—Continued

9. Maurice Ewing and Edward Titus Miller, "Geomagnetic Measurements in the Gulf of Mexico"
10. A. P. Crary, "Some Unique Features of Seismic Operations on Arctic Ice"
11. J. Tuzo Wilson, "A Structural Analysis of the Major Ranges, Fracture Systems and Basins of the Cordilleran and Appalachian Systems"
12. Author to be Announced, "The Economics of Geophysical Exploration in the Gulf of Mexico"
13. Leo A. Markley, "Geophysical Case History of Grand Isle Field"
14. Robert C. Stone, "Geophysical Case History of Sharon Ridge Canyon Field"
15. R. W. Mossman, "Interpretation of a Geophysical Prospect"

TUESDAY MORNING, MARCH 29, 1955

Joint Session—Honors and Awards, Presidential Addresses, etc.

TUESDAY AFTERNOON, MARCH 29, 1955

Mining Geophysics Papers

1. Thomas R. Shugart, "Problems of Uranium Exploration"
2. R. A. Broding and Ben F. Rummerfield, "Simultaneous Gamma Ray and Resistivity Logging as Applied to Uranium Exploration"
3. L. C. Pakiser and R. E. Warrick, "The Shallow Reflection Seismograph in Mining, Engineering and Ground-Water Investigations"
4. Kenneth E. Burg, "Applications of High Frequency Seismic Recording"
5. Roland G. Henderson and Isidore Zietz, "The Graphical Calculation of Total-Intensity Anomalies of Three-Dimensional Bodies"

6. Oscar Weiss, "Combined Geological, Geophysical and Geochemical Exploration for Copper and Lead Deposits in Northern Rhodesia"
7. Hans Lundberg, "Results of Airborne Radioactive, Electromagnetic and Magnetic Surveys"

WEDNESDAY MORNING, MARCH 30, 1955

Geophysical Logging and Seismic Velocity Papers

1. H. R. Breck, S. W. Schoellhorn and H. M. Thralls, "Acoustic Logging and Its Geophysical and Geological Applications"
2. M. R. J. Wyllie, A. R. Gregory and L. W. Gardner, "Elastic Wave Velocities in Heterogeneous and Porous Media"
3. Norman R. Patterson, "Seismic Wave Propagation in Porous Granular Media"
4. F. P. Kokesh, "The Long Interval Method of Measuring Seismic Velocity"
5. W. Bailee, "The Effect of Topography on Near-Surface Velocities"
6. Louis W. Gardner, "The Treatment of Lateral Velocity Variations in Seismic Interpretations"
7. P. F. Southwick, K. S. Spiegler, and M. R. J. Wyllie, "The Application of a Three Component Model to the S.P. and Resistivity Phenomena Evinced by Dirty Sands"

WEDNESDAY AFTERNOON, MARCH 30, 1955

New Geophysical Methods and Geophysical Research Papers

1. R. L. Palmer, "A New Seismic Technique and Results to Date"
2. Jack Oliver, Frank Press and Maurice Ewing, "Seismic Model Studies"
3. V. Baranov, "A New Method of Interpretation of Aeromagnetic Maps: Pseudo-Gravimetric Anomalies"
4. F. A. Collins and C. C. Lee, "Seismic Wave Attenuation Characteristics from Pulse Experiments"
5. Paul Farren and Vining T. Reynolds, "The Reynolds Plotter"
6. Hal J. Jones, "Seismic Applications of Some New Filtering Techniques"
7. Carl H. Savit, "The Moveout Filter"
8. J. P. Woods, "The Composition of Reflections"

EDUCATIONAL EXHIBITS

Arrangements are being made for the display of educational exhibits at the annual meeting of the American Association of Petroleum Geologists and the Society of Exploration Geophysicists in the Hotel Statler, New York, March 28 through 31, 1955.

A generous amount of space has been reserved for exhibits by colleges, universities, professional societies, geological surveys, and similar non-commercial organizations.

Those considering the preparation of educational or scientific exhibits are advised to communicate with the Chairman of the Educational Exhibits Committee before December 15, 1954.

PAUL F. KERR, Chairman
Educational Exhibits Committee
for New York Convention
Columbia University
Department of Geology
New York 27, New York

STUDENT EMPLOYMENT INTERVIEW CENTER

A Student Employment Interview Center will be in operation in the Skytop of the Statler Hotel during the New York meeting, March 28, 29, 30 and 31. Students seeking employment in geology, geophysics, or paleontology may avail themselves of this service by filling out interview forms and arranging schedules at the Center.

A letter describing the employment service is being sent to oil, geophysical, and service companies, state and federal surveys, and to colleges offering courses in geology, geophysics, and paleontology. Information for posting on college bulletin boards is also being supplied.

The committee feels the employment service will be particularly useful this year because of the large number of eastern colleges not regularly visited by employers' representatives. Prospective employers who wish to participate should contact John C. Maxwell, Chairman, Student Employment Committee, 1955 Convention, Dept. of Geology, Princeton University, Princeton, New Jersey

PERSONAL ITEMS

SIGMUND HAMMER, head of the gravity interpretation section, Gulf Research & Development Co., and a past president of the SEG, will present a paper at the Fourth World Petroleum Congress in Rome next June.

MAYNARD P. JONES has returned to an active status in domestic operations for Exploration Seismic Inc. as Vice-President in charge of domestic operations. In this capacity he will supervise the firm's operations seismic crews and will engage in augmenting the research and interpretative staff of the company.

H. R. THORNBURGH, regional geophysicist for Shell Oil Co., Pasadena, California, received the company's diamond-set service emblem and a gold watch when he completed 25 years of service last summer.

D. T. GERMAIN-JONES is chief geophysicist of Anglo-Iranian Oil Co., Ltd., Beaufort House, Gravel Lane, London, E. 1, England.

CHARLES H. HUFFMAN is now seismic sales engineer for Houston Technical Laboratories.

Establishment of a new geophysical office for Stanolind Oil and Gas Company at Jackson, Mississippi, has been announced. The office will be located on the 14th floor of the Standard Life Building in Jackson, where Stanolind also has a district exploration office for land and geological operations. The geophysical group will number 19 persons, bringing to 47 the total number of Stanolind exploration department employees headquartered in Jackson. D. W. RATLIFF, field seismograph supervisor, will be in charge of both the Jackson and Oklahoma City geophysical offices. His headquarters will continue to be in Oklahoma City.

Operational headquarters of Geomarine Service International, Inc., offshore exploration division of GSI, moved from Dallas to New Orleans September 7, 1954. Office address in New Orleans will be 512 Carondelet Bldg. NEIL W. MANN has been made manager of Geomarine, replacing CURTIS H. JOHNSON. Johnson has been transferred to Holland as resident director of Geophysical Service (Nederland) N. V. Mann has held the position of assistant manager in the Geomarine Dallas Office for the past year.

Establishment of a new geophysical office for Stanolind Oil and Gas Company at Denver, Colorado, has been announced. G. L. ELLIS, field seismograph supervisor, will be in charge of both the Denver and Casper geophysical offices. His headquarters will continue to be in Casper.

H. A. SEARS, President of Electrotechnical Labs., Inc., announces the creation of a research and development division under direction of DR. R. W. LONG with additional new personnel in E. L. OGLESBY, P. C. SUNDT, R. T. ROACH, F. REYNOLDS, S. HATCHL. Laboratory facilities are at 522 Waugh Drive, Houston, Texas.

Stanolind Oil and Gas Company's district exploration office at Tyler, Texas has been augmented by a geophysical staff. The transfer of JACK L. MATAYA, staff geophysicist, and JACK W. ESTES, intermediate geophysicist, from Lubbock to the Tyler office, located in the Fair Building, will bring to thirty the total number of Stanolind exploration department employees in Tyler.

In Stanolind's North Texas-New Mexico Division there are, in addition to the Tyler office, geophysical offices in Abilene, Lubbock, and Midland, Texas, and Roswell, New Mexico. J. D. NOVOTNY, field seismograph supervisor, will be in charge of the geophysical office at Tyler as well as the other four geophysical offices. His headquarters will continue to be in Lubbock.

ROBERT C. HERRON has transferred from Gulf Research & Development Co. at Pittsburgh, Pa. to Gulf Oil Corporation, Box 1290, Fort Worth, Texas. His present title is assistant division geophysical supervisor.

CHARLES E. GREENER has resigned from Sun Oil Company to join Texas Petroleum Company in Caracas, Venezuela as a geophysicist.

S. T. FEE has resigned as Oklahoma division manager for William Ross Cabeen & Associates to open an office as an exploration consultant at 217 Braniff Building, Oklahoma City, Okla.

JOHN L. FERGUSON is now Vice-President and manager of exploration for Buffalo Oil Company, First National Building, Tulsa, Okla.

JOHN W. ERICKSON, formerly with Chemical & Geological Lab., Inc., Casper, is now a geologist with the Gulf Oil Corporation, Box 1971, Casper, Wyoming.

LYNN D. ERVIN has joined Geophysical Consultants, Inc. as Vice-President. He was formerly division geophysical supervisor for Stanolind Oil & Gas Company.

M. W. HARDING, United Geophysical Corp., Box M., Pasadena 15, California, has duplicate copies of GEOPHYSICS, Vol. II, No. 4 (October, 1937) and Vol. XII, No. 3 (July, 1947), one of which he would like to trade for a copy of Vol. XIII, No. 1 (January, 1948).

TWO SCHOLARSHIPS IN GEOPHYSICS, of $300 each, have been given to the University of Houston by Sohio Petroleum Company. The first awards were to be made during the 1954 fall term.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912, AND MARCH 3, 1933 of GEOPHYSICS, published quarterly at Menasha, Wisconsin for January 1955.

State of Oklahoma } ss.
County of Tulsa }

Before me, a Notary Public in and for the State and county aforesaid, personally appeared Colin C. Campbell, who, having been duly sworn according to law, deposes and says that he is the Business Manager of GEOPHYSICS, and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business managers are: Publisher, Society of Exploration Geophysicists, 624 S. Cheyenne, Tulsa, Oklahoma; Editor, Milton B. Dobrin, Box 900, Dallas 1, Texas; Business Manager, Colin C. Campbell, 624 S. Cheyenne, Tulsa, Oklahoma.
2. That the owner is: Society of Exploration Geophysicists, 624 S. Cheyenne, Tulsa, Oklahoma.
3. That the known bondholders, mortgagees, and other security holders owning or holding 1 per cent of more of total amount of bonds, mortgages, or other securities are: None.
4. That the two paragraphs next above, giving the names of the owners, stockholders, and security holders, if

any, contain not only the list of stockholders and security holders as they appear upon the books of the company but also, in cases where the stockholder or security holder appears upon the books of the company as trustee or in any other fiduciary relation, the name of the person or corporation for whom such trustee is acting, is given; also that the said two paragraphs contain statements embracing affiant's full knowledge and belief as to the circumstances and conditions under which stockholders and security holders who do not appear upon the books of the company as trustees, hold stock and securities in a capacity other than that of a bona fide owner; and this affiant has no reason to believe that any other person, association, or corporation has any interest direct or indirect in the said stock, bonds, or other securities than as so stated by him.

5. That the average number of copies of each issue of this publication sold or distributed, through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is ————————. (This information is required from daily publications only.)

COLIN C. CAMPBELL (Signed)

Sworn to and subscribed before me this 30th day of September, 1954.
[SEAL]

EUNA W. ROGERS (Signed)
(My commission expires November 22, 1954.)

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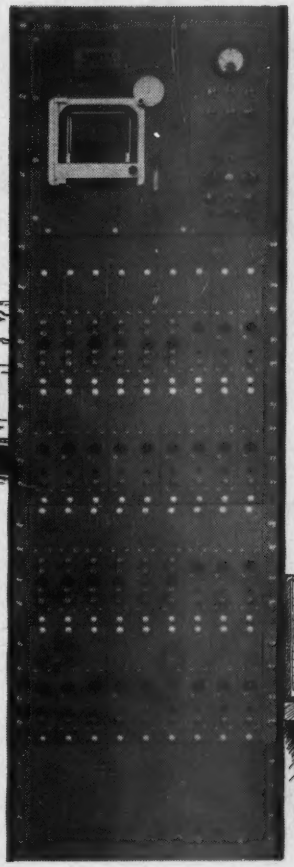

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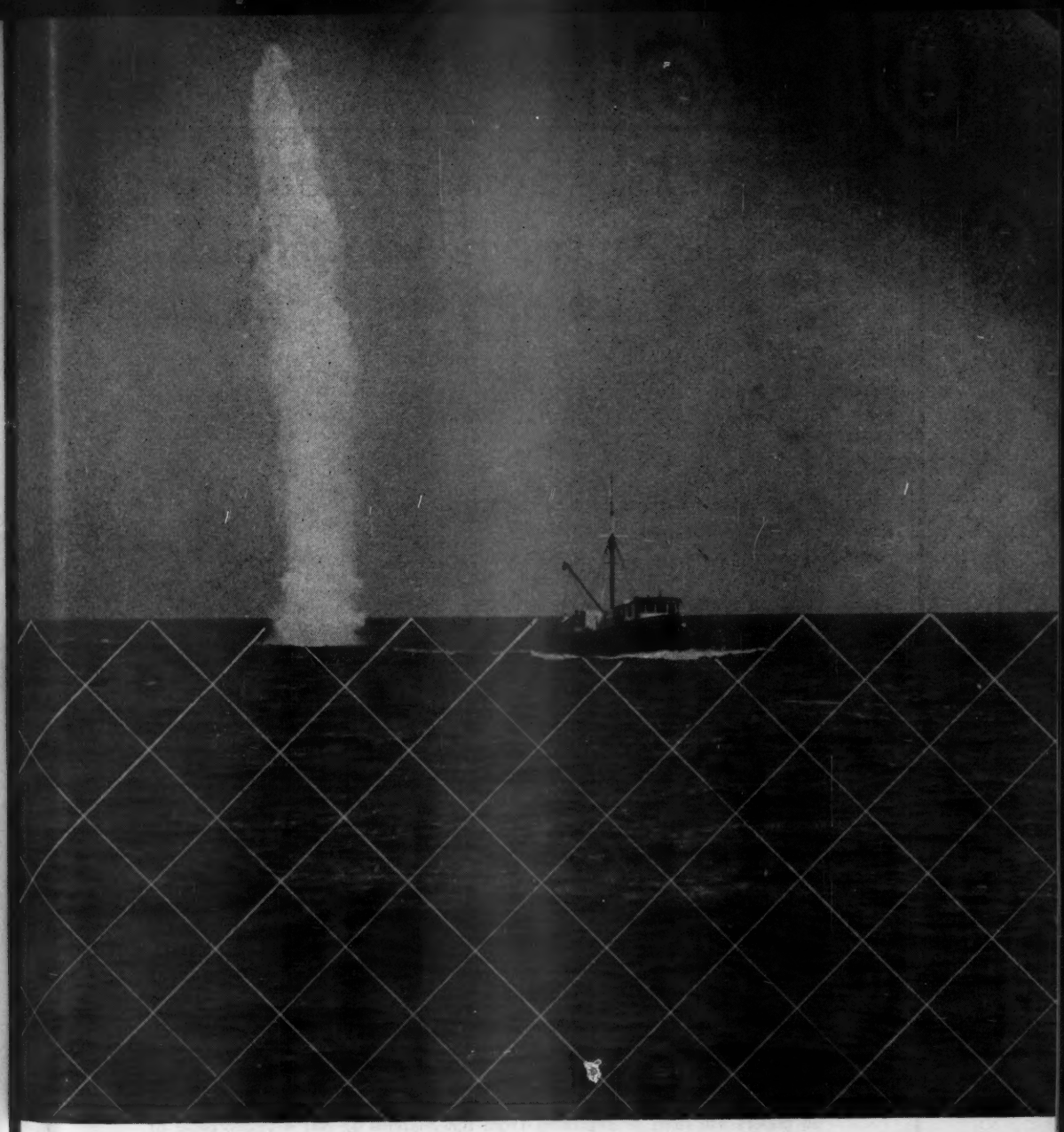

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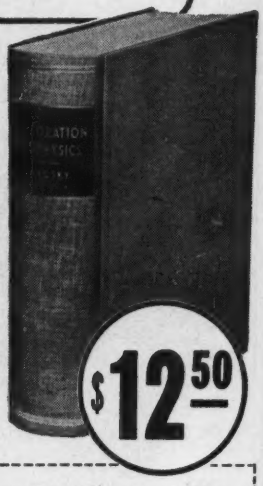

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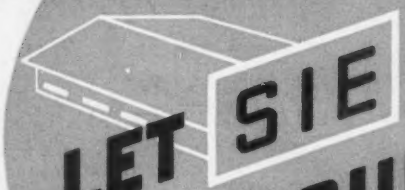

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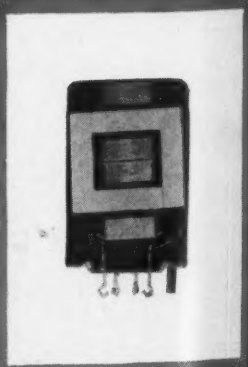

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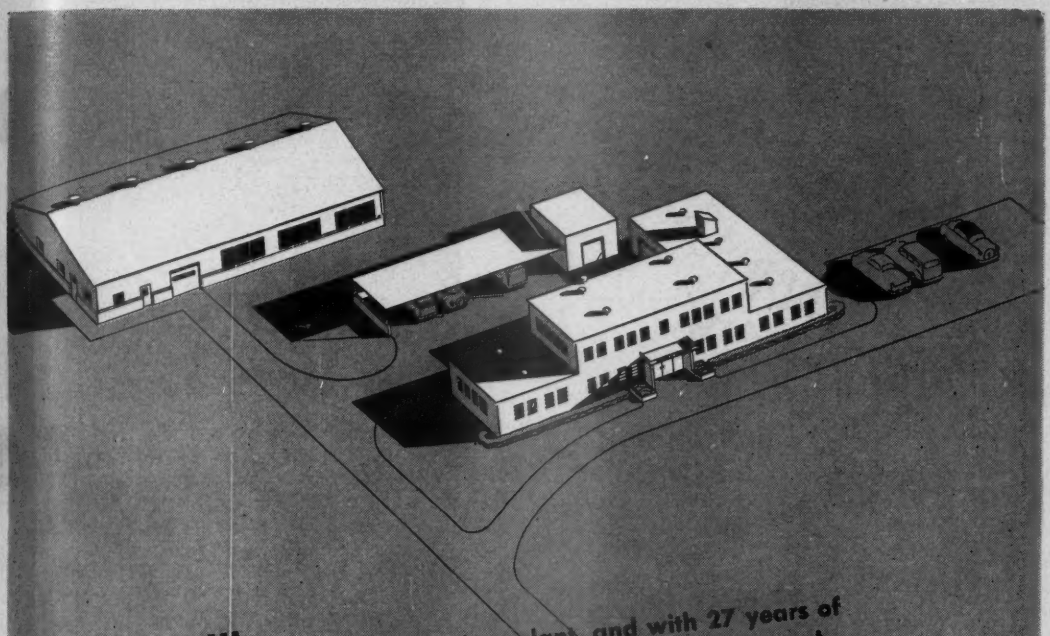

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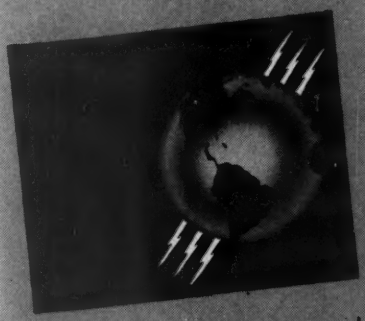

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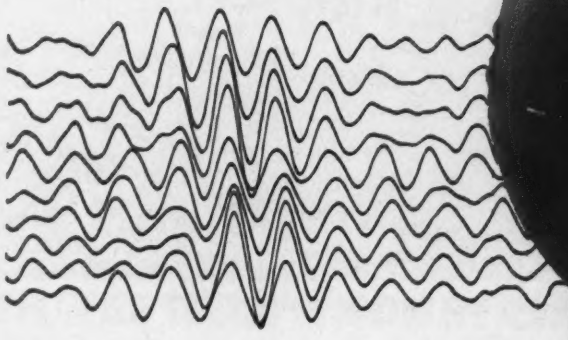

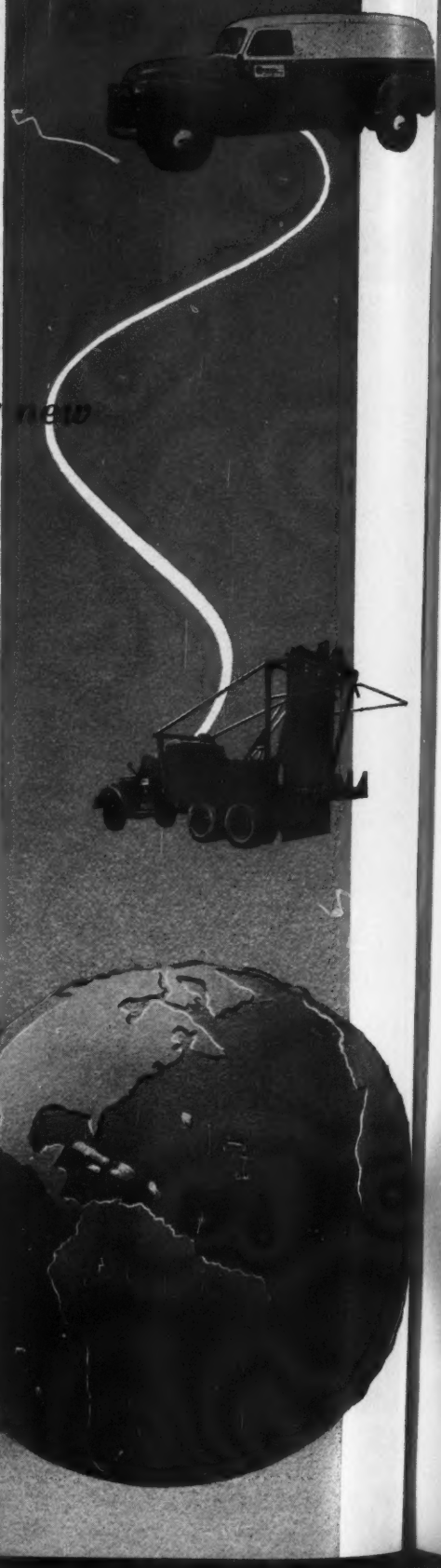

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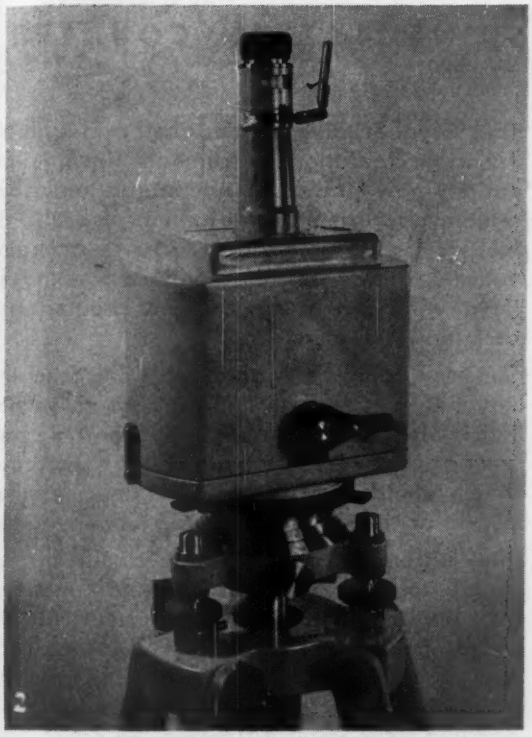

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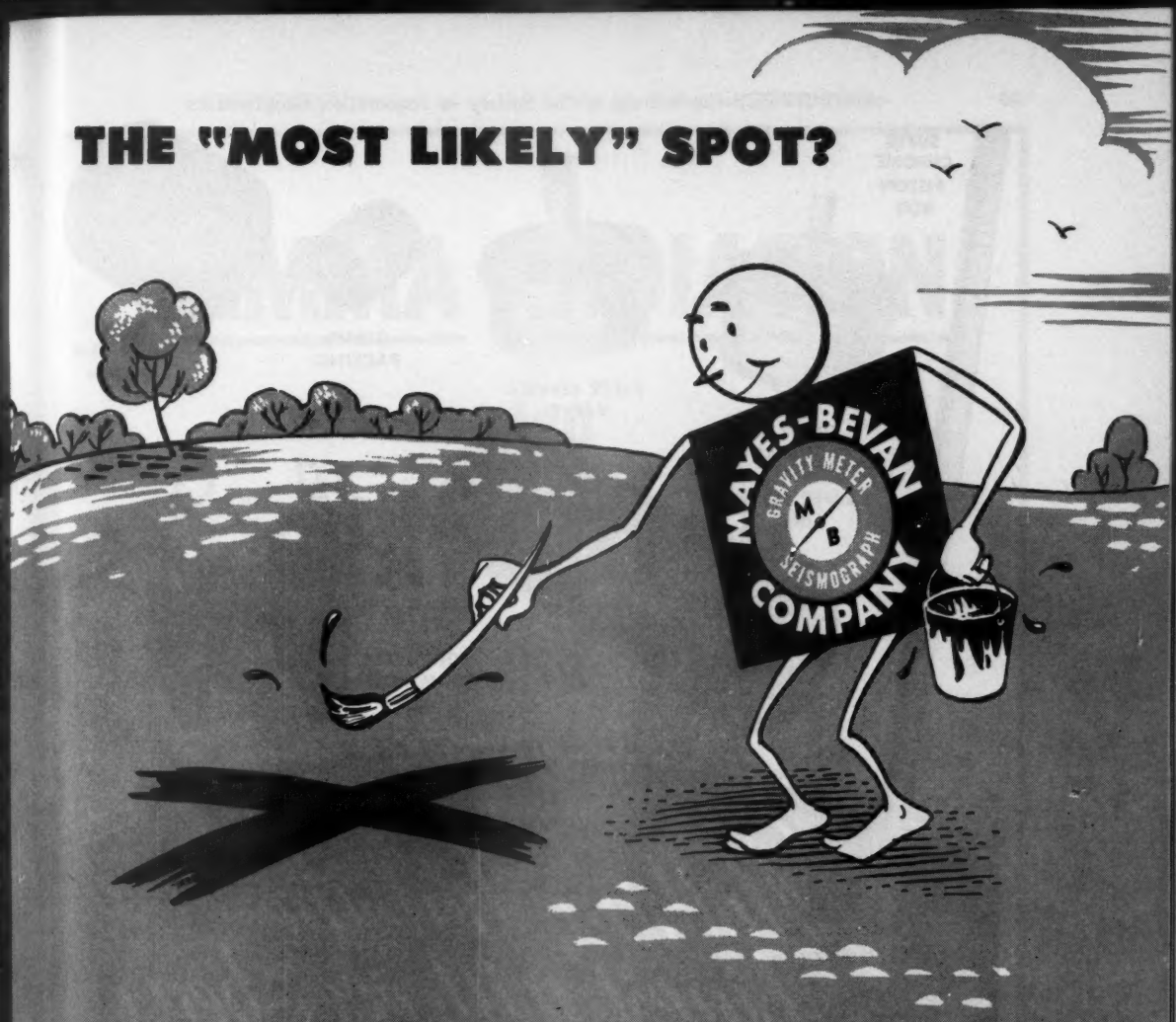

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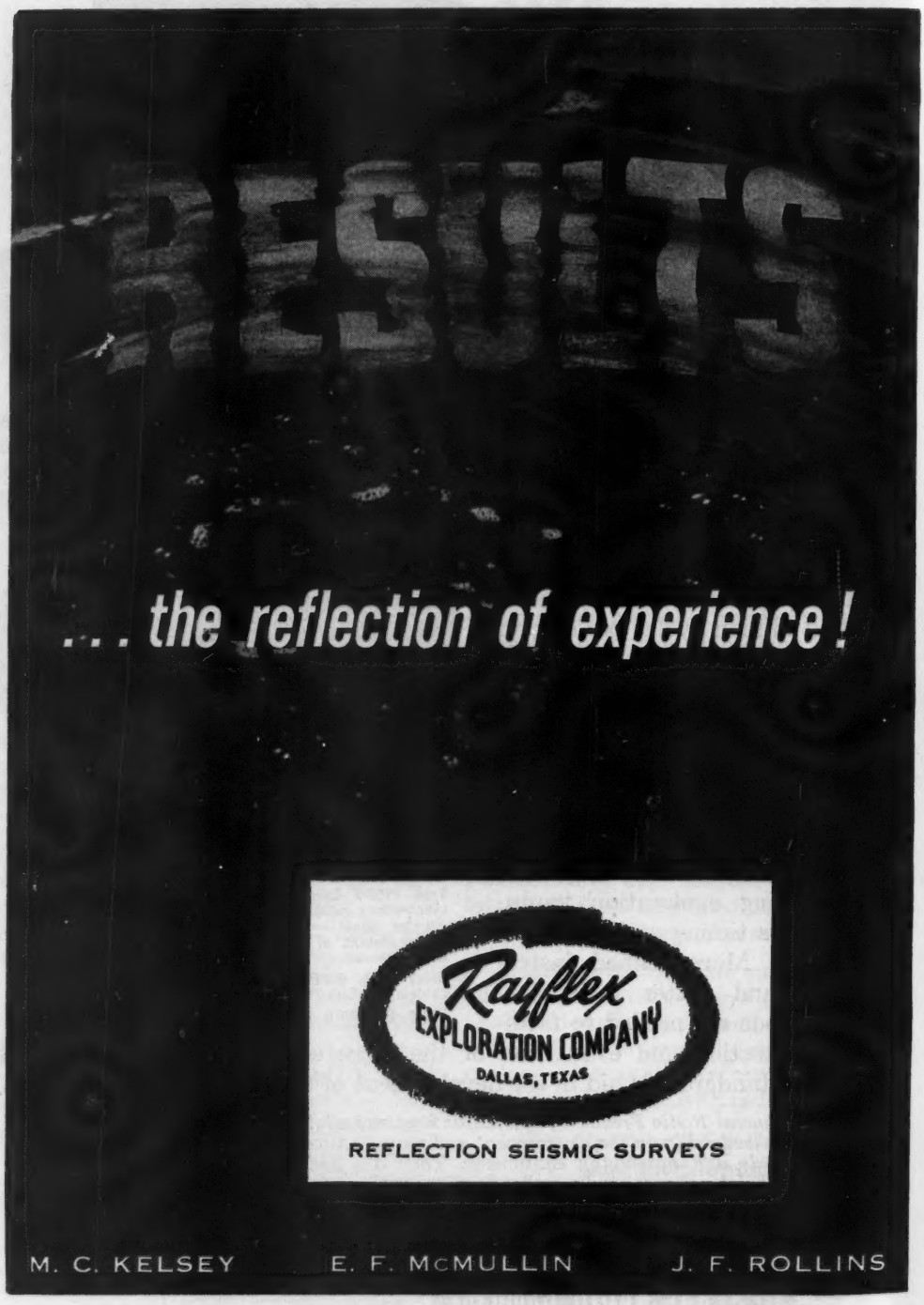
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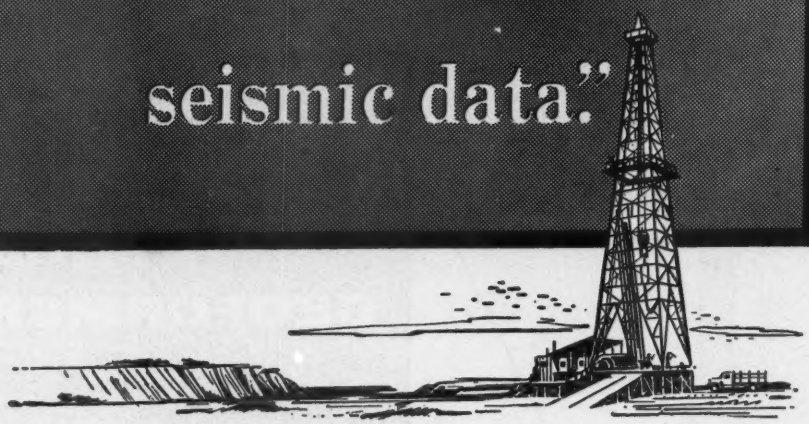

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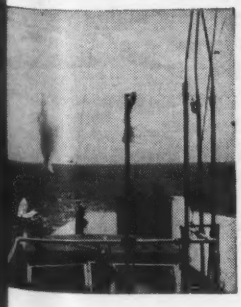

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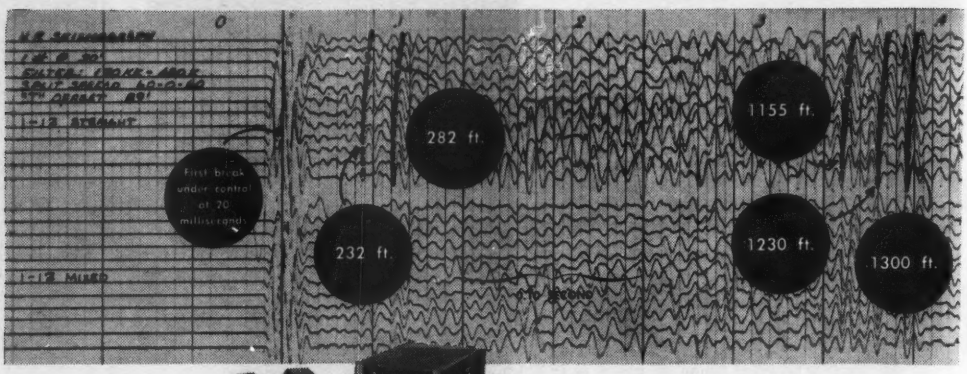

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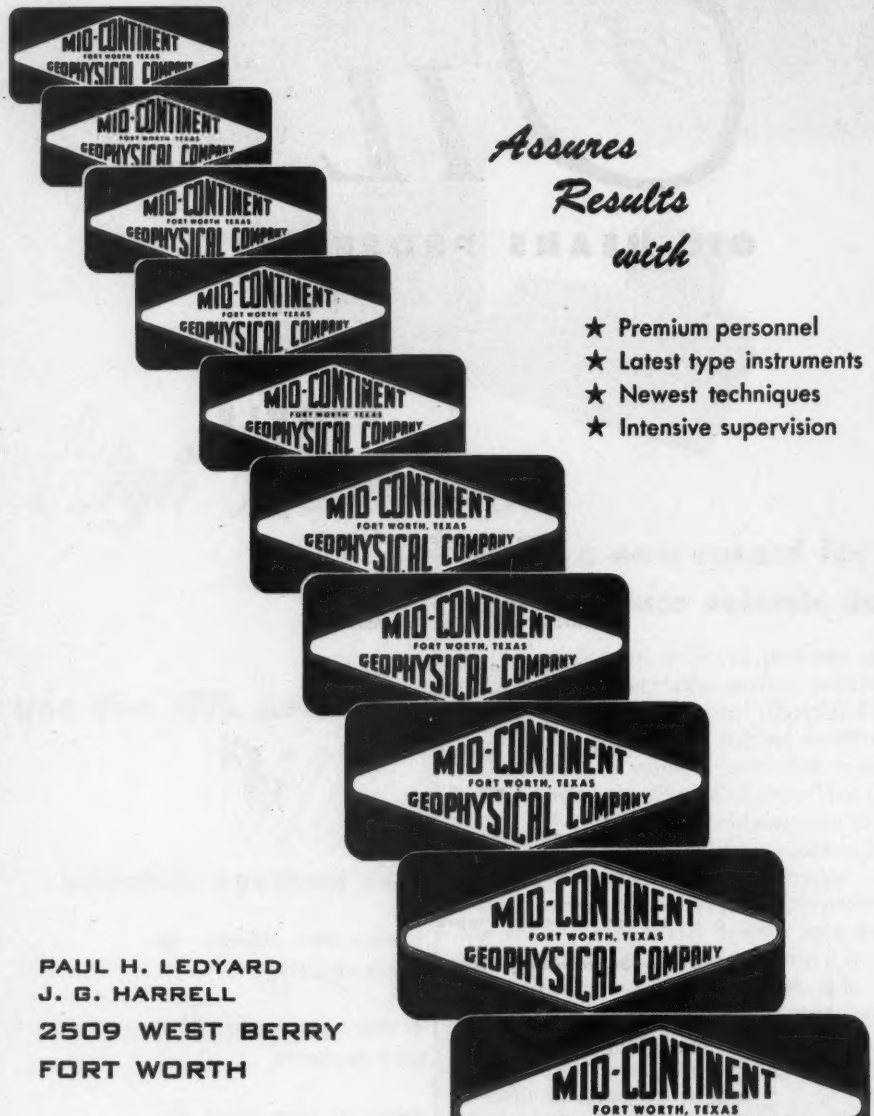

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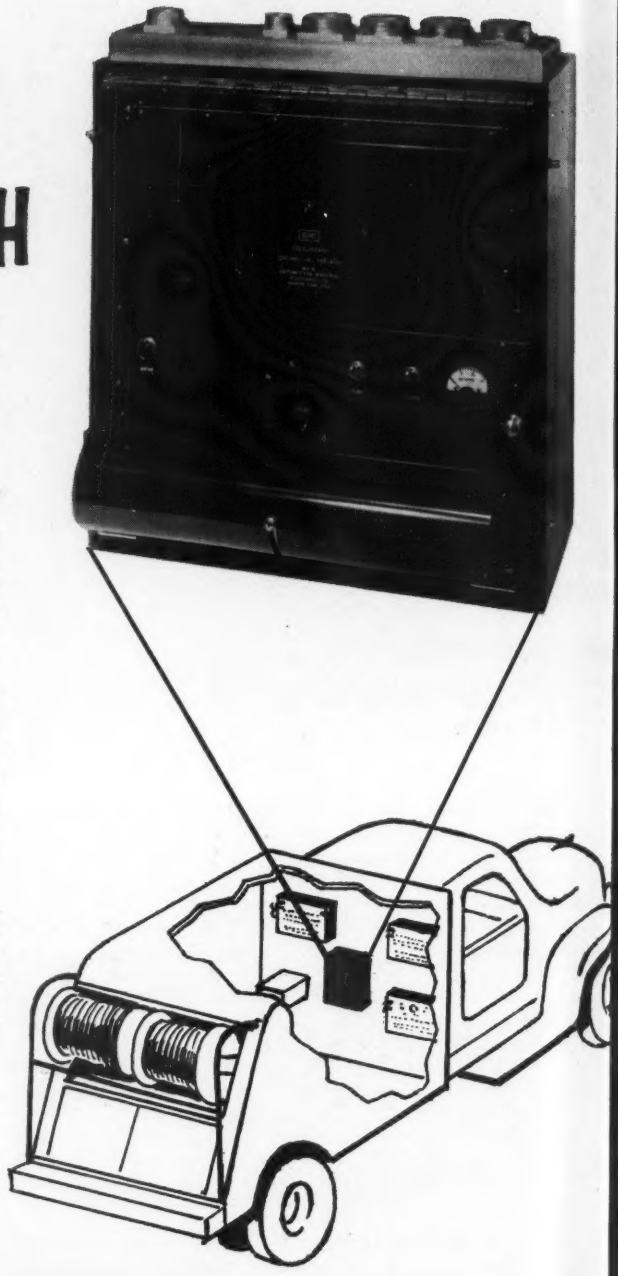

The new PRO-11-12 Recording Oscillograph answers the industry demand for a compact, light-weight instrument accepting 12-inch recording paper. The wide paper allows conventional presentation of dual records and permits wider galvanometer spacing to minimize "trace cross-over" in all multi-channel recording applications.

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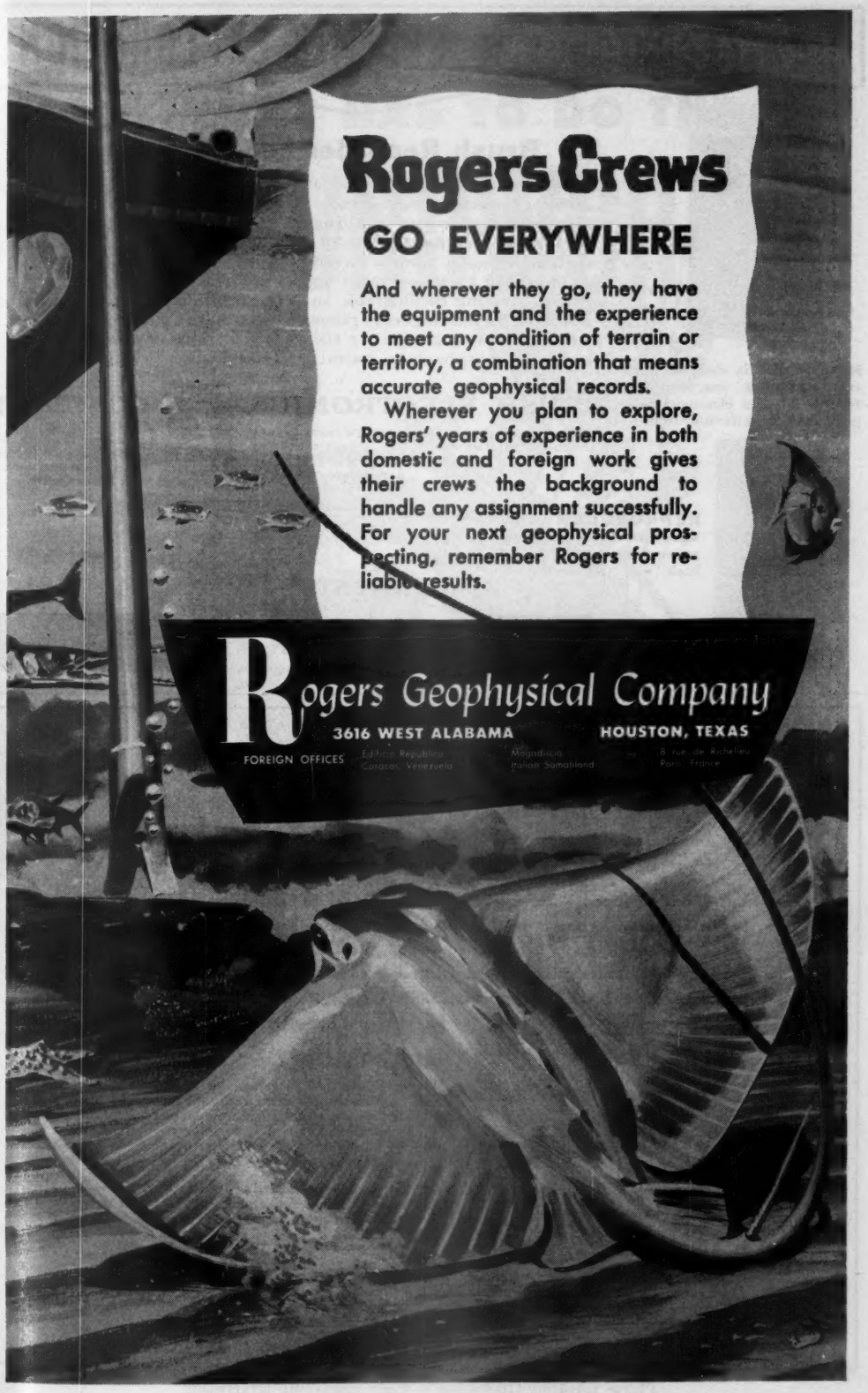
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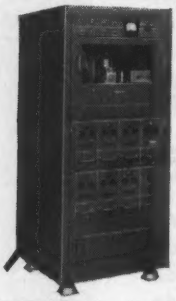

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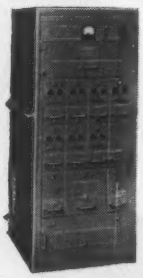

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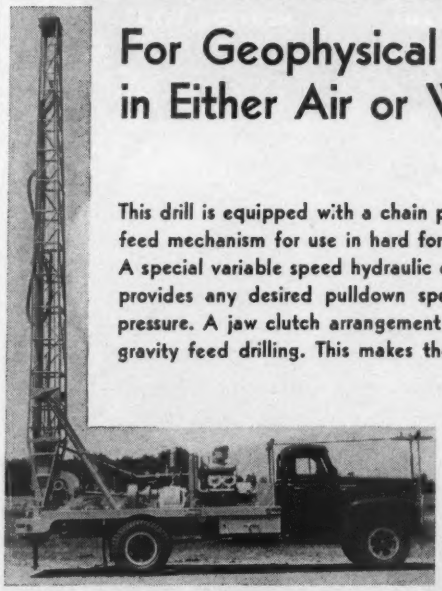

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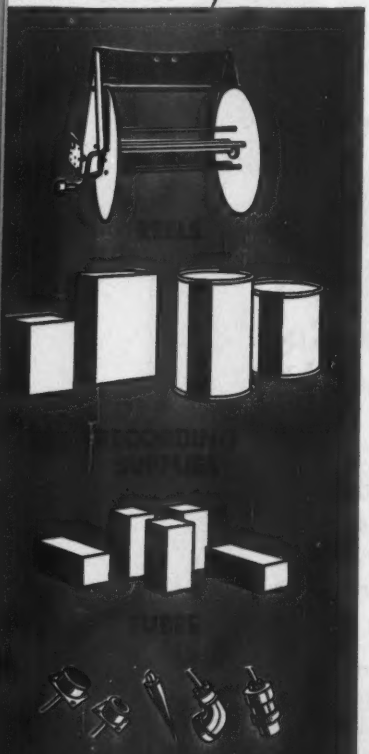

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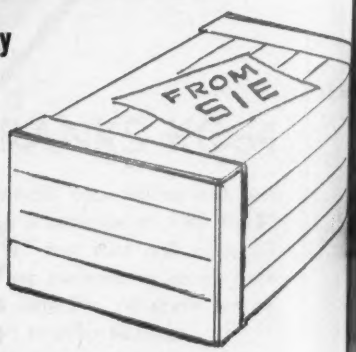

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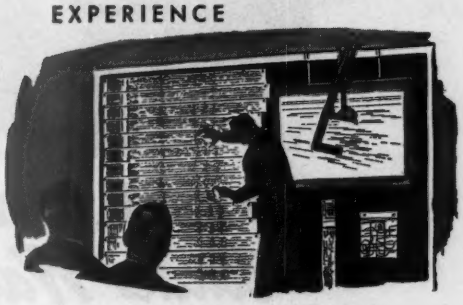

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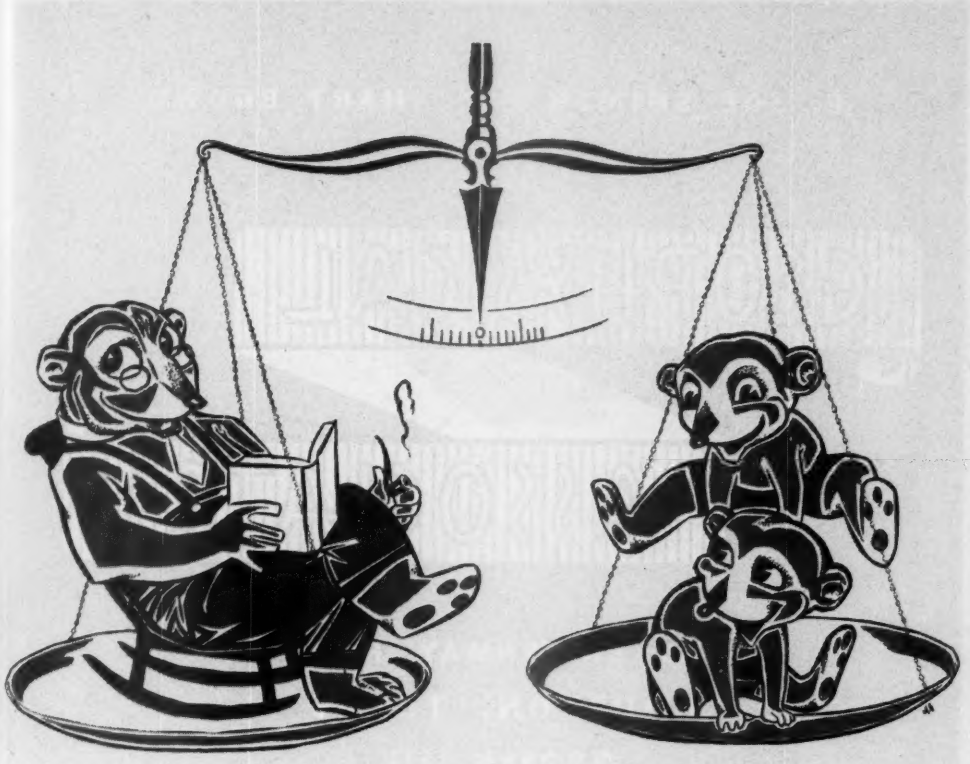

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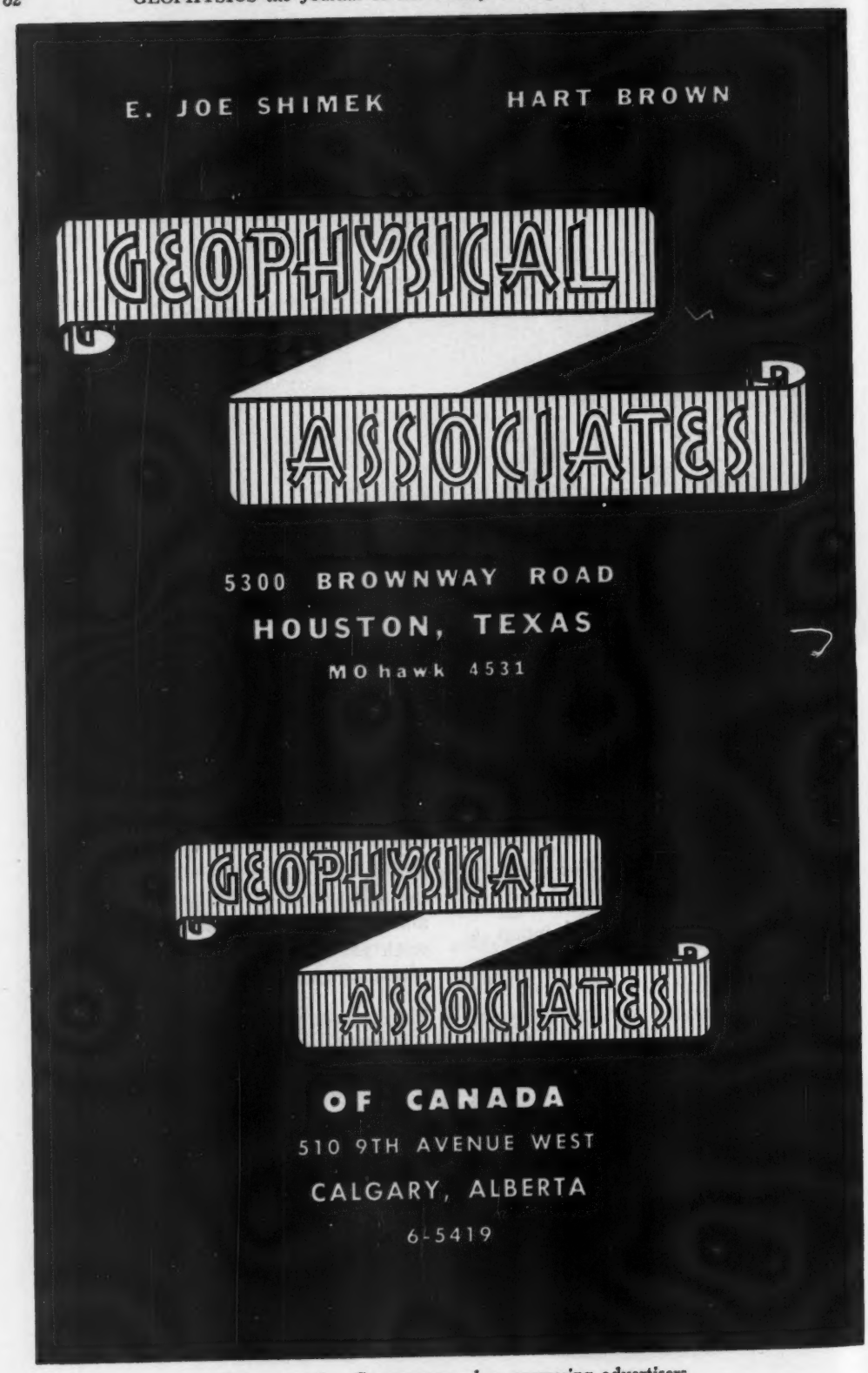

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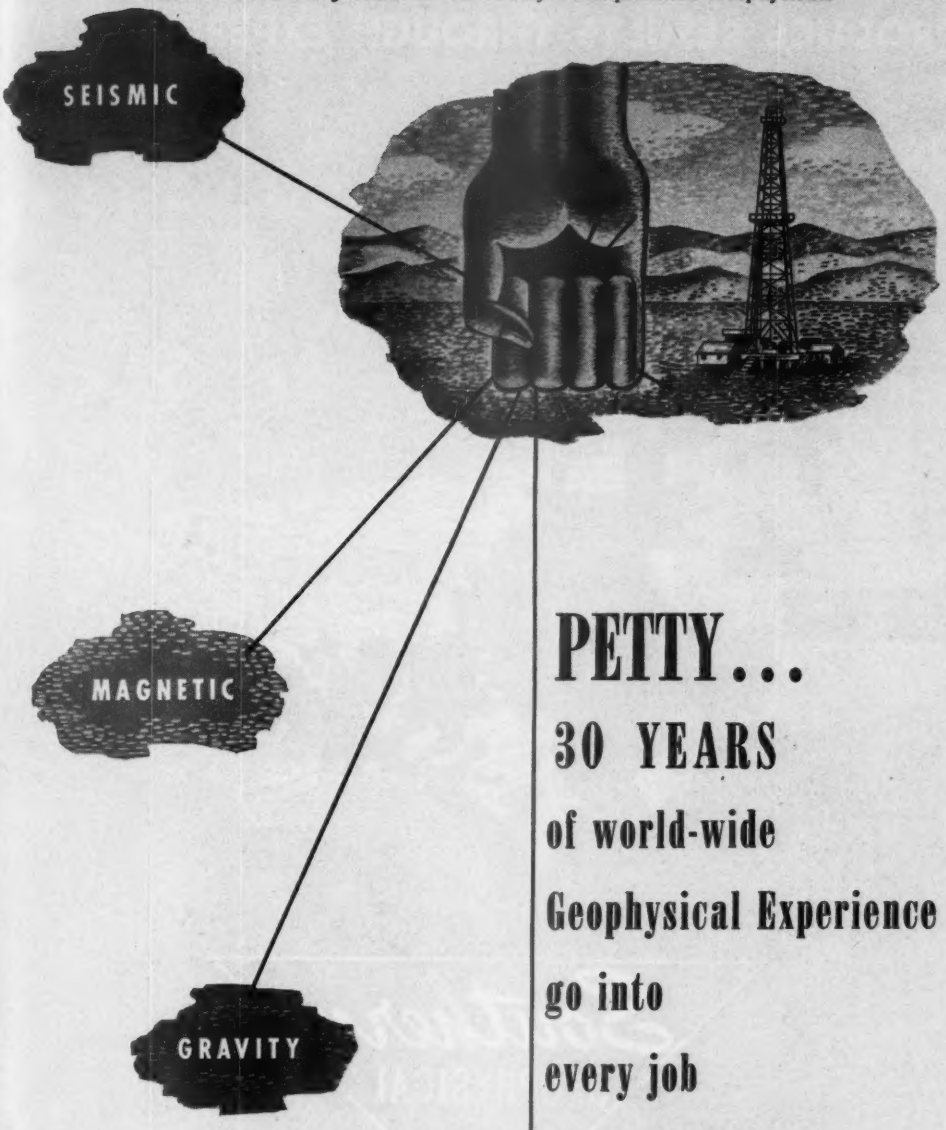

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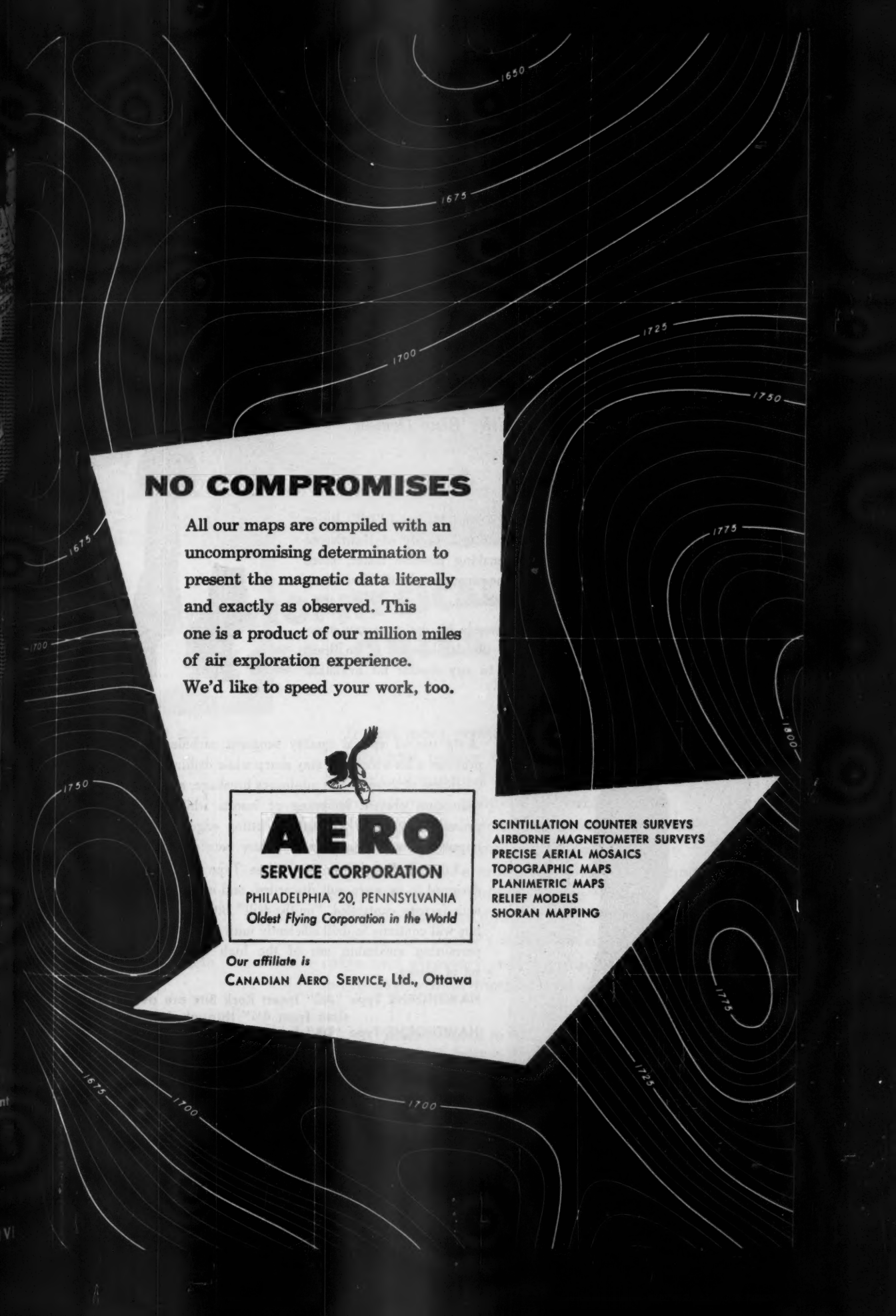

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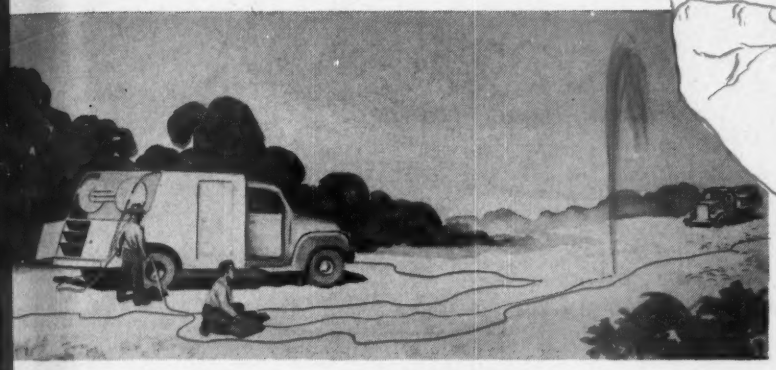

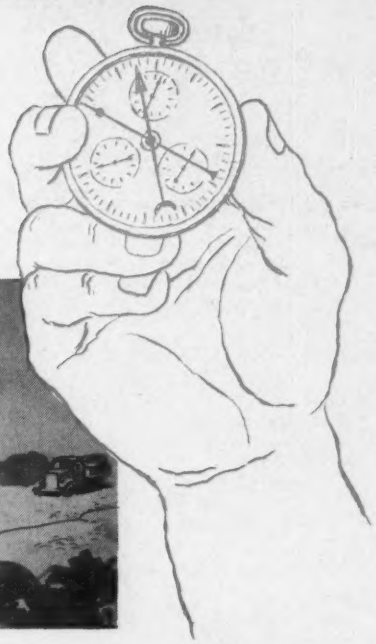

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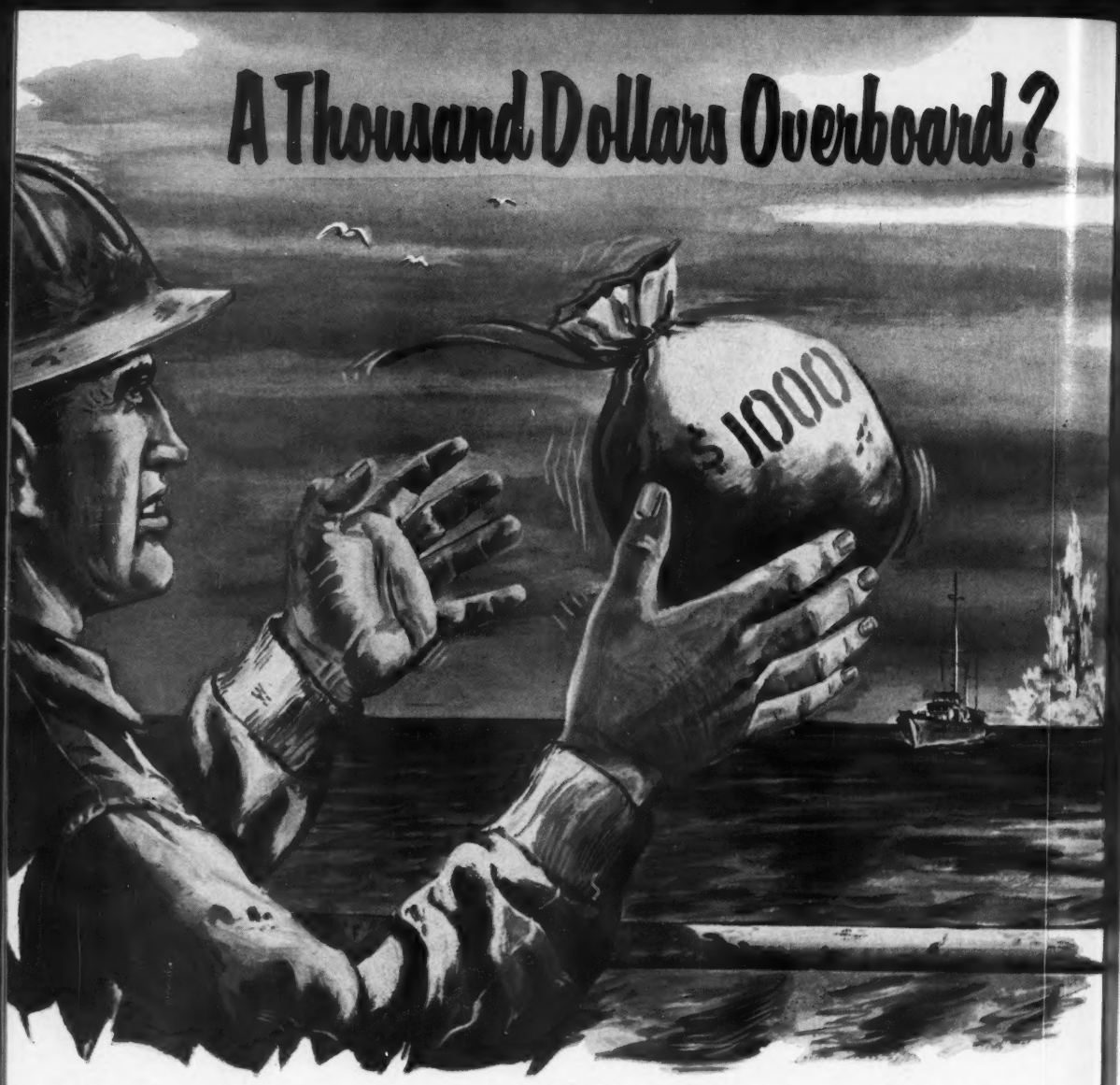

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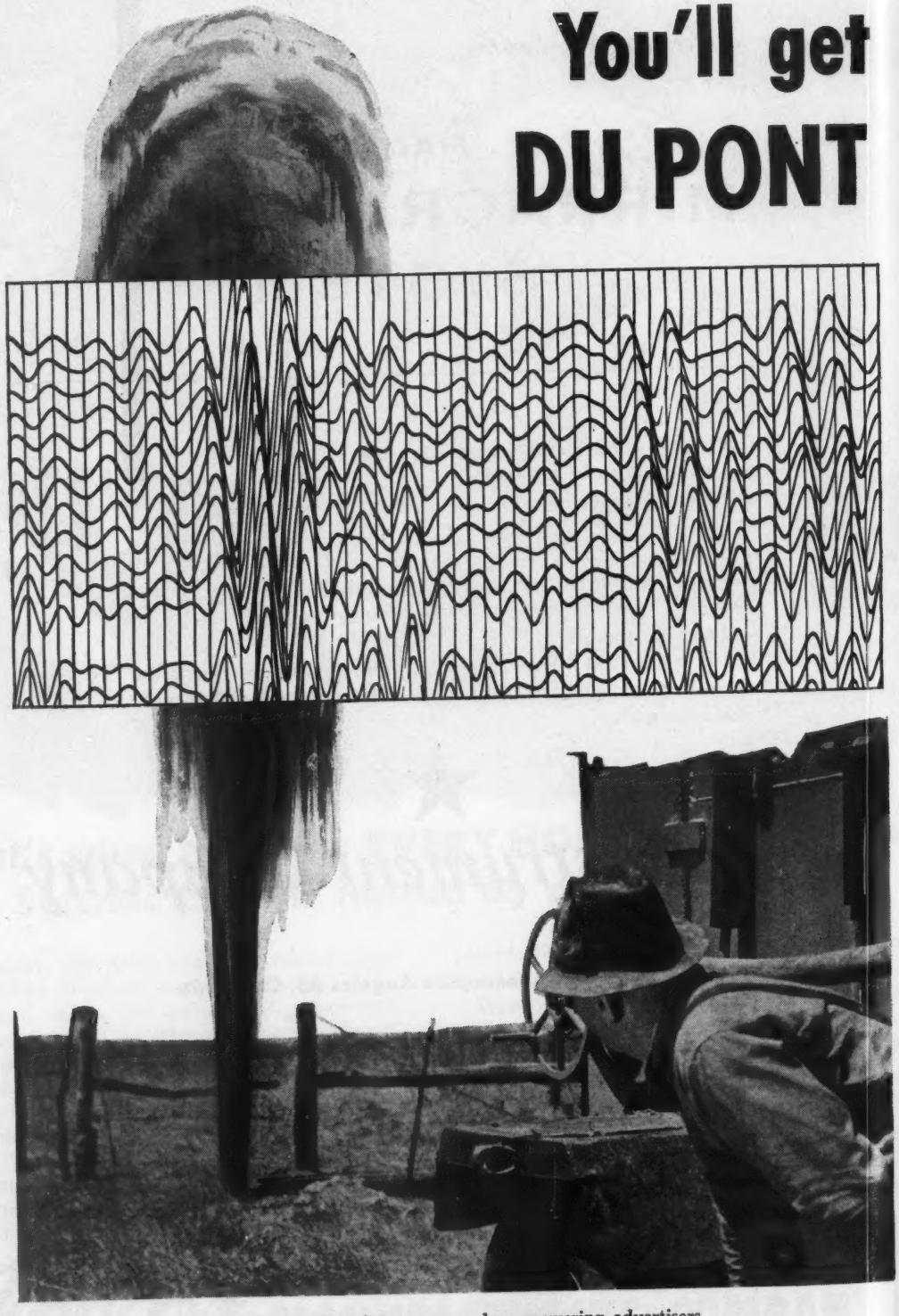

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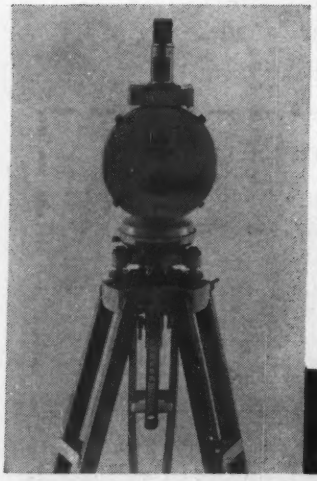

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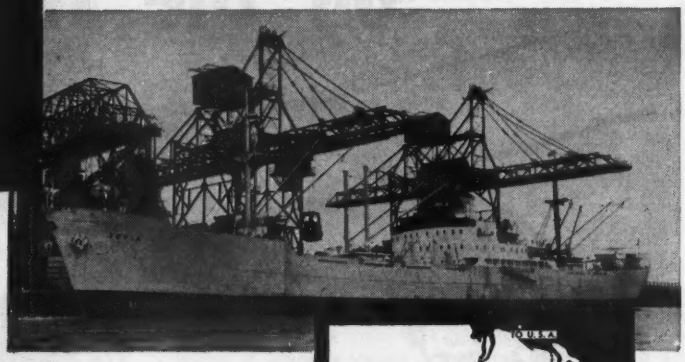

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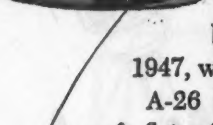

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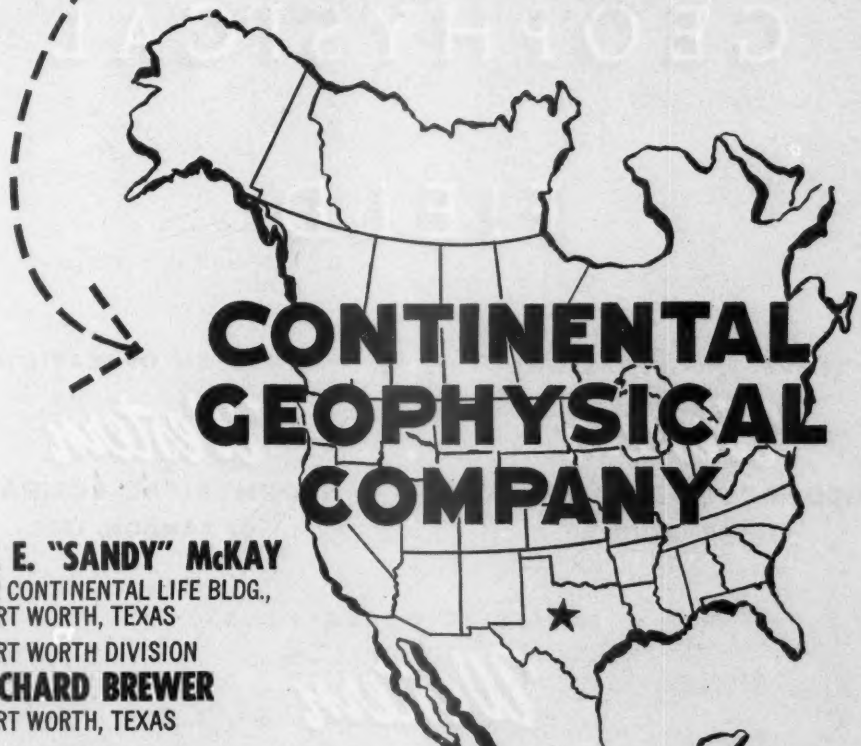

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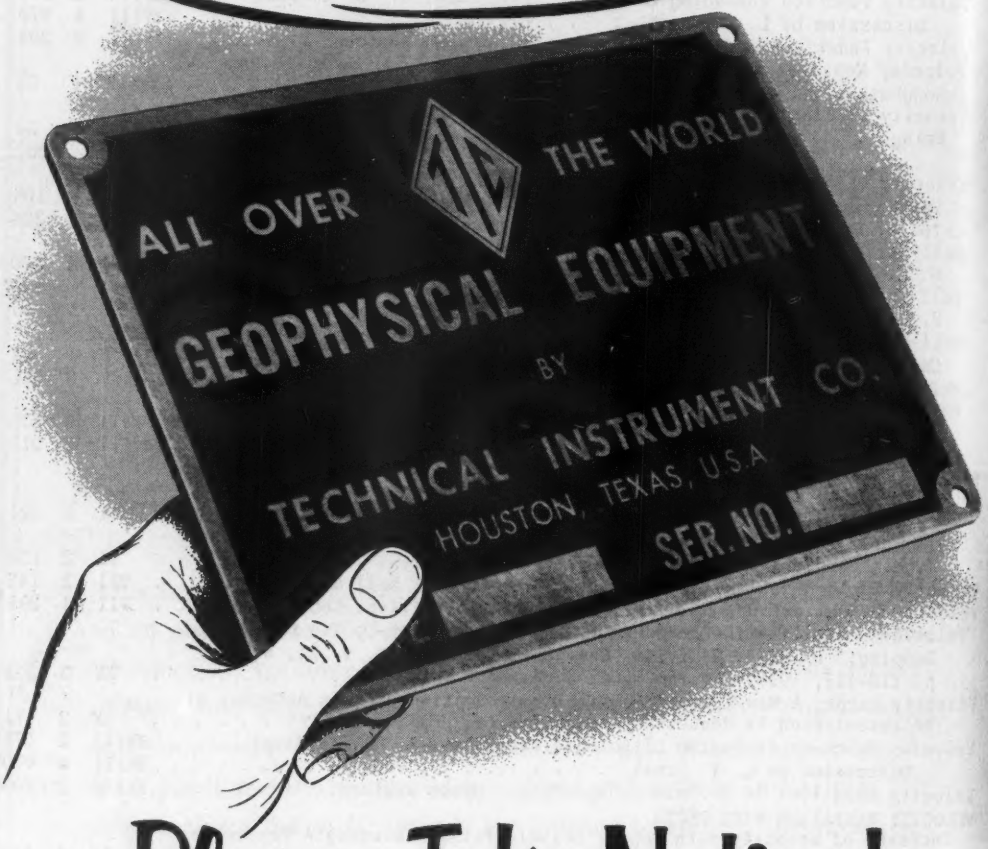

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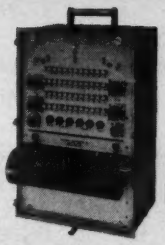

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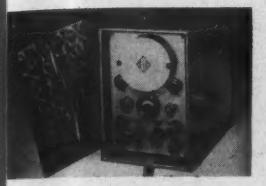

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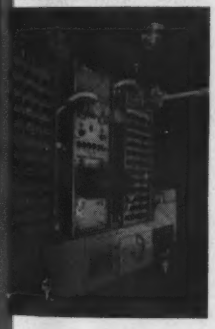

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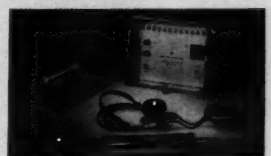
DEEP WELL SEISMOMETER

Fitted with one vertical and two horizontal seismometers at 90° this Deep Well Seismometer, 241-W, has been used beyond 15,000 feet in making horizontal structure studies and standard velocity surveys. Conventional vertical type velocity phones are available. This and all TIC seismometers are warranted against defective materials and workmanship for six months on a free replacement or repair basis.



CABLE FAULT DETECTOR

The "troubleshooter" — TIC Cable Fault Detector—successfully locates faults in both portable and power reel cables. Light, compact with transmitter and receiver store as one unit, the 80 hour life battery is protected with momentary switches. Size 7" x 9" x 6".

ecording, water and ng trucks are custom- o your requirements.

MARSH SEISMOMETER

Used in multiple strings, the TIC Marsh Seismometer, 241-54, simplifies field checking. Here expensive external strain members may be eliminated since conductors and anchor are rated at 300 lbs. tensile strength. Fitted with a solid brass or aluminum housing case. A waterproof plug-in connection with an "idiot proof" method of polarization. These seismometers are getting records in some areas previously considered NR (no record). 1½" x 6" — wt. 20 oz. — any reasonable length leads provided.

PORTABLE REELS

TIC portable reels are built for long life and hard usage. Operated on sealed ball bearings with tight canvas straps to protect users from metal, they are available in 9" and 13" flange diameters.

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